PB-238 695

# A STUDY OF TECHNOLOGICAL IMPROVEMENTS IN AUTOMOBILE FUEL CONSUMPTION

## VOLUME IIIA: APPENDIXES I THROUGH III

ARTHUR D. LITTLE, INCORPORATED

PREPARED FOR
TRANSPORTATION SYSTEMS CENTER
ENVIRONMENTAL PROTECTION AGENCY

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16. Abstract

A study was conducted to determine potential improvements in automobile fuel consumption based on innovative design and components. Standard and compact-size reference vehicles were selected, and a study of how power is used was conducted. Obvious technological innovations (e.g., powerplants (such as spark-ignited, turbocharged, stratified charge, electronic fuel injected, and diesel), transmissions and drive train systems, tires, accessories and auxiliaries, aerodynamics, and weight) that would save on fuel consumption were identified and evaluated, and then screened against program constraints. Operation of reference vehicles equipped with innovative components or redesigned was computer-simulated to predict fuel usage and performance. Techniques to measure fuel economy performance were also developed, and a statistical evaluation of published driving modes was performed. Compliance of innovative components with constraints (such as emissions and safety) and user requirements was determined. Optimized synthesized standard and compact-size vehicles were simulated and total systems evaluation of each vehicle was performed on the basis of fuel usage, performance, technical compatibility, compliance with constraints, user acceptability, and manufacturer adaptability. Synthesized vehicles were ranked in accordance with study objectives, and conclusions and recommendations on designs were drawn. Program plans for synthesized vehicles were also selected.

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# APPENDIX I

# GENERAL DATA

## APPENDIX I-1 SUMMARY OF SOURCES AND TYPES OF DATA COLLECTED

| DATA DESCRIPTION | AUTO & ENGINE MANUFACTURERS | SUPPORT INDUSTRIES AND INDEPENDENT EXPERTS | SOURCE LITERATURE DATE |
|---|---|---|---|
| REFERENCE VEHICLE DATA | | | |
| Fuel Economy | 5 | 12 | 18 |
| Performance | 5 | 11 | 12 |
| Engine Maps | 4 | 8 | 8 |
| Accessory & Auxiliaries | 5 | 6 | Listed under Accessory Drive below |
| Drive Line Components | 4 | 10 | Listed Under Transmission & Drive Train below |
| Aerodynamic Drag | 4 | 2 | 16 |
| Weight | 5 | 2 | 12 |
| ENGINE DATA | | | |
| Lean Burn | 3 | 8 | 15 |
| Stratified Charge | 2 | 4 | 20 |
| Diesel | 7 | 4 | 9 |
| Turbocharged Engines | 2 | 4 | 7 |
| TRANSMISSION & DRIVE TRAIN | 4 | 9 | 43 |
| FUEL SYSTEMS & ELECTRICAL | 6 | 10 | 18 |
| ACCESSORY DRIVE | 2 | 3 | 12 |
| AIR CONDITIONERS | 4 | 2 | 8 |
| TIRES | 4 | 3 | 6 |
| CONSTRAINTS | 4 | 7 | 10 |
| DRIVING CYCLES | 4 | 6 | 12 |
| OPERATING CONSIDERATIONS | 4 | 5 | 21 |

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## APPENDIX I-2 SAMPLE QUESTIONNAIRE

SUBJECT:

TITLE AND NAME OF PAPER:

ADL FILE NO.:

DESCRIPTION OF IMPROVEMENT:

DESCRIPTION SUMMARY:

STATE OF DEVELOPMENT:

PRESENT PROBLEMS:

FUEL ECONOMY AND EMISSION RESULTS:

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PERFORMANCE RESPONSE:

CHANCES OF SUCCESS STATED OR
IMPLIED BY WRITER:

COMPLEXITY:

INITIAL COST ESTIMATE:

OPERATING COST ESTIMATE:

AVAILABILITY WITHIN TIME FRAME
OF DEMONSTRATION:

TIME TO IMPLEMENT TO MASS PRODUCTION:

ENVELOPE SIZE:

WEIGHT:

EFFECT ON OTHER SUBSYSTEMS:

DURABILITY:

RELIABILITY AND MAINTENANCE:

COMPLIANCE WITH CONSTRAINTS:

POTENTIAL FOR GROWTH:

CONCLUSIONS AND REMARKS:

ROUGH DRAFT

By

Date

CLASSIFICATION

## APPENDIX I-3

## CHARACTERISTICS OF THE COMPOSITE CAR

### 1. Specifications

For the purposes of this study we have developed two composite passenger vehicle specifications: one for a compact weight class, and one for standard weight class. The specification covers mainstream automobiles manufactured by each of the major producers of the industry. The specification for each of these classes will be used as the reference vehicle for collection of performance information and also will be used as a benchmark for the measurement of improvements proposed to gain improved fuel economy. The details of the specifications are listed below and are to be used as a guide. Minor deviations are acceptable for submittal of data.

| COMPACT PASSENGER VEHICLE | SPECIFICATION |
|---|---|
| Year | 1973 Models |
| Body style | 4-door sedan |
| Include options | Automatic transmission, power steering |
| Shipping weight | 2,750 to 3,200 lbs. |
| Curb weight (including options) | 2,860 to 3,400 lbs. |
| Wheel base | 108" to 111" |
| Axle ratio | 2:76 to 3:23 |
| Standard tires | 6:45-4, E78-14, belted or bias |

| COMPACT PASSENGER VEHICLE | SPECIFICATION |
|---|---|
| Engine: | |
| No. of cylinders | 6 |
| CID | 225 to 250 cu. inches |
| Rated horsepower | 88 to 105 HP @ 3,200 to 4,000 RPM |

| STANDARD PASSENGER VEHICLE | SPECIFICATION |
|---|---|
| Year | 1973 Model |
| Body style | 2-door hardtop |
| Standard equipment | Automatic transmission, power steering |
| Include options | Air conditioning |
| Shipping weight | 3,800 to 4,480 lbs. |
| Curb weight (including options) | 3,900 to 4,500 lbs. |
| Wheel base | 120" to 122" |
| Axle ratio | 2:71 to 3:23 |
| Standard tires | F78-15, G78-15, belted or bias |
| Engine data: | |
| No. of cylinders | 8 |
| CID | 350 to 400 cu. inches |
| Rated horsepower | 145 to 200 HP @ 3,800 to 4,000 RPM |

## 2. SPECIFIC PERFORMANCE CHARACTERISTICS

To assist in processing the reference vehicles and improvement ideas to evaluate fuel economy, we require performance data for each of the reference vehicles.

We recognize that the performance data is recorded in various formats by the industry manufacturers, and therefore, the way in which the data is presented will vary. However, the list presented below is offered as a guide to the essential data which we require to model performance; and if the data is recorded in other formats we need the various pieces to allow us to determine the power and fuel economy for the vehicle and its components.

### A. Engine Maps

(1) Brake horsepower or torque vs. engine RPM with a family of curves relating to various manifold vacuums from idle to wide open throttle (WOT).

(2) Specific fuel consumption (BSFC) vs. engine RPM for the same range of vacuums as above.

### B. Vehicle Resistance

Total resistance of the vehicle for steady speed level road operation (either a force or power) as a function of road speed. The data should separate the tire rolling resistance, aerodynamic drag, wheel bearings, rear axle, differential and drive shaft.

C. Polar Moment of Inertia

Polar moment of inertia of engine and drive train components-- This data should include for the engine with and without accessories, the torque converter, gear box, drive shaft, differential, axles, including all wheels and tires.

D. Torque Converter and Transmission Performance

(1) Performance data on torque converter to determine input/output speed ratio and torque ratio as a function of input speeds and torque.

(2) Gear box ratios, and loss characteristics as a function of speed and load.

(3) Shift pattern data as a function of speed, throttle position, and vacuum also require definition of the relationships between the speed, vacuum, and throttle position.

E. Rear Axle Performance

(1) Axle efficiency as a function of speed and load.

(2) Rear axle ratio.

F. Accessory Power Requirements

Horsepower required to drive each of the following components: radiator fan, air conditioning equipment, alternator, power steering pump, and air pump as a function of speed over the operating load range.

G. Fuel Economy Measurements

Measured fuel economy in MPH over EPA/CVS driving cycle and at steady speed level road conditions for 20, 30, 40, 50, 60, and 70 MPH. Applicable climatic data should be included.

## 3. FUEL CONSUMPTION DATA AND COMPONENT POWER BREAKDOWN

In order to validate the results obtained from the computer model analysis of the performance data supplied for item #2 above, we require average fuel consumption data for each of the various driving modes listed below: first, as a complete vehicle; secondly, subdivided with the fuel consumption broken into the various power train components within the vehicle. (The average should be defined as for a single vehicle, a group of vehicles, or a statistical average including standard deviation.)

In addition to the above, for the standard class automobile only, we require data with and without the air conditioning in operation.

For each of the modes listed below, data covering developed power, power absorbed by component, emission level, and fuel usage are required.

A. Based on constant volume sample, the EPA/CVS urban dynomometer driving schedule;

B. Warm engine, constant speed operation at each of the following speed levels: 20, 30, 40, 50, 60, and 70 MPH;

C. Idle conditions as follows:

   (1) Hot engine idle at ambient temperature of 70°F and other appropriate temperatures;
   (2) Cold engine idle at ambient temperature of 70°F and other appropriate temperatures.

D. Starting conditions as follows:

(1) Cold engine start at 70°F and other appropriate ambient temperatures for first minute and until automatic choke opens;

(2) Hot engine start at 70°F and other appropriate ambient temperatures for first minute and until automatic choke opens.

In addition we require data on WOT operation at the acceleration modes as follows:

| ACCELERATION LEVEL (MPH) | ELAPSED TIME | DISTANCE TRAVELED |
|---|---|---|
| 0 - 30 | | |
| 0 - 60 | | |
| 25 - 70 | | |

| ACCELERATION LEVEL (MPH) | ELAPSED TIME | TERMINAL SPEED |
|---|---|---|
| 0 - 440' | | |
| 0 - 1/4 mile | | |
| Duty passing maneuver (C.F.R. Vol. 49, pg. 549, Oct. 1, 1972, paragraph 575106) | | |

## 4. INNOVATIVE DEVICE DESIGN

Within the framework of the approach presented in the cover letter, would you comment on each of the innovative ideas listed that appear to have the most promise to improve fuel economy within the constraints imposed on the industry by 1976 time frame. Please add to and adjust the list as you desire and rank ideas in any order you feel most appropriate as the ideas are just listed without preference to ranking gains in fuel economy or ranking desirability.

The intent here is to determine which of the concepts the industry feel are most appropriate and promising to meet the goals of fuel economy and have the most desirable tradeoffs for production of the passenger vehicles.

We would appreciate any definitive information and data to support your position which do not jeopardize your competitive position.

### INNOVATIVE IDEAS

- Accessories
  - Radiator fan
    - Flex fan
    - Viscous clutch drive
    - Mechanical slip clutch drive
    - Electric drive

- Power steering
  Reduce unloaded power loss.
- Air conditioning
  Absorption refrigeration cycle
  Conventional system with improved drive
- Accessory drive systems
  Constant speed drive
  Waste heat Rankine cycle drive
  Exhaust turbine drive
- Intake and exhaust system
  Tuning

- **Engines**
  - Light weight diesel
  - Stratified charge engine
  - Small base engine with boost
    Super charger
    Turbo charger
    Boost and variable compression ratio piston
  - Engines with specific fuel consumption improvements
    Fuel injection
    Ultrasonic carburetors
    Improved carburetors
  - Engine friction and air induction loss--reduce parasitic friction and flow losses.

- Transmission
  - -- Automatic transmission modifications

    Hydraulic pump constant speed drive

    Torque converter
  - -- IVT --engine/load matching

- Other
  - -- Ignition improvement--electronic ignition

    Higher spark energy and duration
  - -- Regenerative braking--hydraulic accumulator stores energy from braking to help re-accelerate vehicle.
  - -- Tires-radial.

## APPENDIX I-4

## PERSONS AND ORGANIZATIONS CONTACTED FOR PERTINENT DATA

| | |
|---|---|
| Prof. John Heywood | Massachusetts Institute of Technology |
| Wayne Anderson | U.S. Army Tank-Automotive Command<br>Warren, Michigan |
| Peter Huntley | Orshansky Transmission Corp.<br>New York |
| James Francischina | Chrysler Corp., Detroit, Michigan |
| George J. Heubner, Jr. | Director of Research<br>Chrysler Corp., Detroit, Michigan |
| Ernest Upton | General Motors Technical Center<br>Warren Michigan |
| Donald Stivender | General Motors Technical Center<br>Warren, Michigan |
| Donald McPherson | General Motors Technical Center<br>Warren, Michigan |
| William Route | General Motors Technical Center<br>Warren, Michigan |
| Dr. Craig Marks | General Motors Technical Center<br>Warren, Michigan |
| Wayne M. Brehob | Ford Motor Company<br>Dearborn, Michigan |
| Donald Jensen | Ford Motor Company<br>Dearborn, Michigan |
| David Hwang | Ford Motor Company<br>Dearborn, Michigan |
| Clayton LaPointe | Ford Motor Company<br>Dearborn, Michigan |
| Marvin Stucky | Vice President Engineering<br>American Motors, Detroit, Michigan |

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| | |
|---|---|
| Harold M. Siegel | Assistant to Vice President Engineering<br>American Motors, Detroit, Michigan |
| Gerald Meyer | Group Vice President Production<br>American Motors, Detroit, Michigan |
| Robert A. Petersen | Director Advanced Power Plants & Research<br>American Motors, Detroit, Michigan |
| Daniel Hittler | American Motors, Detroit, Michigan |
| L.A. Schaefer | Product Development Engineer<br>Vehicle Fabrication Department<br>American Motors, Detroit, Michigan |
| D.R. Hahnke | Supervisor, Road Test Department<br>American Motors, Detroit, Michigan |
| Prof. Jay A. Bolt | Automotive Engineering Department<br>University of Michigan |
| J.W. Holdeman | Engineering Manager, New Products Development<br>Warner Gear |
| Walter Lassiter | Assistant Director of R & D<br>Borg-Warner |
| Walter Fisher | Borg-Warner |
| George Kochaner | Borg-Warner |
| Irv Hallberg | Borg-Warner |
| George Burton | Program Manager of Advanced Automobile Concepts Program, Bendix-General |
| Charles Bailey | Universal Oil Products |
| William Paynton | Texas Instruments, Inc. |
| Dr. Ernest Jost | Texas Instruments, Inc. |
| Richard Delagi | Texas Instruments, Inc. |
| W.E. Clinger | Alcoa-Pittsburgh |
| Robert Kewory | Alcoa-Boston |

| | |
|---|---|
| Thomas McAllister | Alcoa-Washington, D.C. |
| J.L. Riederick | Alcoa-Pittsburgh |
| Paul F. Jolie | Alcoa |
| Ben Cole | Raytheon Company |
| Richard Syson | Teledyne Continental Motors |
| James H. Kraus | Project Engineer, Tracor, Inc. |
| Robert Guedet | Engineering, Sundstrand Aviation |
| C.E. Capron | Engineering, Sundstrand Aviation |
| Max Roensch | Consultant<br>Birmingham, Michigan |
| Frederick Hooven | Consultant<br>Norwich, Vermont |
| James Dooley | Vice President<br>McCulloch Corp., Los Angeles, Calif. |
| James Cole | President<br>Hydro-Catalyst Corp.<br>Affiliate of F.D. Farnum Co. |
| Cecil French | Ricardo and Company |
| Murray Scott | Ricardo and Company |
| J. Preagle | President, Autotronic Controls Corp. |
| Gaines M. Crook | Gaines M. Crook and Associates<br>Consulting Engineers<br>Canoga Park, Calif. |
| Englert, Robert D.<br>Berriman, L. | Dresser Industries Inc.<br>Environmental Technology Division<br>170 McGaw<br>Santa Ana, Calif. 92705 |

# APPENDIX I-5

## SUMMARY OF PERTINENT FIELD TRIP REPORTS

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# FIELD TRIP REPORT

**COMPANY VISITED** **DATE** 10-5-73

Tracor, Inc.
6500 Tracor Lane
Austin, Texas 78721

**PERSONS SEEN**

Marcel Gres, V.P.
Charles E. Kraus, Consultant
James H. Kraus, Proj. Engr.

**SUBJECT**

TRACOR Continuously Variable Traction Transmission

**GENERAL CONCLUSIONS**

The Tracor traction transmission (CVT) is in an advanced state of development. Significant advances seem to have been made over the GM torroidal drive developed in the 1930's and other similar units. This traction transmission appears to offer a significant improvement in fuel economy over the operating range by decreasing engine speed during normal operation and providing good acceleration performance by rapidly and smoothly increasing engine speed during accelerations.

**SUMMARY OF INFORMATION OBTAINED**

The Tracor traction transmission is a dual cavity torroidal drive unit with a unique mechanical cam type loading technique which provides excellent transient response behavior and avoids the power loss problems associated with hydraulic loading methods. A multiple disc wet clutch is used to connect up to the engine output shaft. Some of the principal features are listed below.

- o Limit of ratio range = 9:1
- o Fast response - can change ratio over full range in about 8-10 resolutions.
- o Gives better acceleration performance than conventional transmission due to fast response in increasing engine speed during accelerations. Therefore can use smaller engine, obtain equal acceleration and improved fuel economy.
- o Good efficiency - In part due to development of new "Santatrac" traction drive fluid by Monsanto.
- o Torroisal units run on sandblasted surface. This plus improved geometry provide substantial increase in life over previous torroidal traction drives.
- o Size and Weight - equal to or 10-15% smaller than present 3 speed automatics.
- o Cost - Airesearch study for EPA shows cost should be essentially equal to present transmission.

**History**

- Traction drive work originally done for Aircraft-Constant speed drive.
- C.E. Kraus had similar units running in Rambler American in early 1960's - program with Curtis Wright. Claims 60% better gas mileage.

**Current Status**

Building up unit to be installed in Fort-Pinto for demonstration. Program is summarized by article in Machine Design Magazine October 18, 1973.

**Fuel Economy and Performance**

Tracor claims (via computer simulation of vehicle performance) that this transmission provides 25-30% increase in MPG and about 30-50% better acceleration compared with a car equipped with equal engine HP and a 4 speed manual transmission. When the traction transmission car is compared with a standard car with higher engine power to provide equal acceleration performance, then the fuel economy of the traction transmission car is about 60% greater than the reference car (for both urban driving and 60 MPH highway driving).

**References**

James H. Kraus "Traction Drive Shows Automotive Promise", Machine Design, October 18, 1973.

# FIELD TRIP REPORT

## COMPANY VISITED

DATE 10-3-73

Autotronic Controls Corp.
6908 Commerce
El Paso, Texas 79915

## PERSONS SEEN

Jack Priegel, Manager

## SUBJECT

Electronic fuel control system utilizing ultrasonic atomozation and precise fuel/air metering by electronic controls.

## GENERAL CONCLUSIONS

Learned about general features of their lean burning system. No good data is available on fuel economy and emissions from carefully controlled tests. Their opinion is that ultrasonic atomization will increase MPG about 5% within the constraint of maintaining recognized emission control.

## SUMMARY OF INFORMATION OBTAINED

The Autotronic Controls "Electrosonic III" system for lean burning is S.I. engines utilizes very accurate air flow metering with a turbine type flowmeter and accurate fuel metering with their "Digipump" proportioning pump. An ultrasonic atomizer is employed for fuel atomization and the entire system is integrated through an electronic computer module called the "Digital Fuel Controller"

At the time of our visit they had systems installed in an Oldsmobile and Chevrolet and were operating them on the roads. They were not able to supply any reliable test data on fuel economy and emissions for comparison against a baseline vehicle. An abortive attempt had been made to test the Oldsmobile at Southwest Research in San Antonio but equipment difficulties occurred with the barometric pressure correction system. It was expected that the problems would be corrected and another attempt made to test the vehicle at SWRI over the FDC and at steady speeds.

Autotronics has supplied their equipment to most of the major automobile manufacturers for test and evaluation. No doubt the best definitive data on system performance has been obtained by the auto companies.

## References

Autotronic Controls Corp., Product Data Sheets -

- o Bulletin APD 200-Electronic III Electronic Fuel Induction System
- o ACO 127 Electronic III - Schematic
- o Bulletin 100 B1 - Air Flow Transducers - Series 100
- o Bulletins 100 C1, 100 D1 - Flow Computer - Models 100C, 100D
- o Bulletins 300A1, 300P1 - Digi Pump
- o Bulletins 400A1, 404A1 - Multiple Spark Discharge Ignition Systems.

# FIELD TRIP REPORT

## COMPANY VISITED

DATE 10-3-73

Dresser Industries, Inc.
Environmental Technology Division
170 McGaw
Santa Ana, California 92705

## PERSONS SEEN

Robert D. Englert, General Manager
Les. Berriman, Director Engineering

## SUBJECT:

The "Dresserator" - A device which allows a lean burning S.I. Engine to meet 1975 emission standards while simultaneously improving fuel economy.

## GENERAL CONCLUSIONS

The "Dresserator" variable venturi system operating at an air/fuel ratio of 18:1 and with a thermal reactor manifold is probably capable of providing a 5-10% improvement in fuel economy, while probably meeting the exhaust emission constraints set for this study (no exhaust catalyst required).

## SUMMARY OF INFORMATION OBTAINED

The "Dresserator" is a form of variable geometry venturi atomizer with means for meeting fuel flow to maintain constant air/fuel ratio.

Dresser claims the following general features

- Provides much better air/fuel ratio control, atomization, and A/F mixing than conventional carburetor.
- Capable of 40:1 turndown ratio - much better than ultrasonic atomizer
- Provides small droplet dias (11 microns avg.) and narrower drop dia range than ultrasonic atomizer.
- Operates at 18:1 A/F ratio, gives 4% Oz in exhaust.

Fuel Economy and Emissions Test Date (FDC) on 1971 Ford Galazie - 351 CID V-8
9:1 Comp. Ratio 4500 Lb. Intertia wt.

| Engine | Fuel Economy MPG over FDC | Emissions - gm/mile HC | CO | NOx |
|---|---|---|---|---|
| Baseline (has vac. adv.) | 10.5 | 1.5-2.2 | 34-39 | 4.2-4.4 |
| Dresserator alone (No spark adv.) | 11-13 | 0.8-1.0 | 6-7 | 1-1.3 |
| Dresserator & manifold reactor | 11 | 0.3 | 4-5 | 1.5 |

Only controlled testing has been over FDC for emissions results. All tests show about 5-10% fuel economy improvement over FDC. All tests conducted with no spark advance. They believe that optimizing spark advance for Dresserator (best fuel economy setting) would give significantly better fuel economy.

**References:**

News Release - "Dresser announces Signing of Agreement with Ford on New Auto Emission Control System", June 21, 1973, Dresser Industries, Inc., Dallas, texas.

# FIELD TRIP REPORT

**COMPANY VISITED** DATE 10-11-73

Bendix Research Laboratories
Bendix Center
Southfield, Michigan 48075

**PERSONS SEEN**

Mr. Geo. Burton, Dir. Automotive P.M. Center
Dr. John Thurin, EFI Program Manager
Mr. Walt. Detweiler
Mr. Vasant Gala

**SUBJECT:** Electronic Fuel Injection EFI

**GENERAL CONCLUSIONS**

An EFI system operating near stoicheometric with a 3 mode catalyst for emission control, can offer about 8% fuel economy improvement over current emission controlled cars. No complete definitive data was available from Bendix to permit an independent analysis of economy improvements. This figure is based on their judgment from this extensive work in this field.

**SUMMARY OF INFORMATION OBTAINED**

EFI systems are described in references 58, 59, 60, 66. They employ timed pulse injection into the intake manifolds (behind each intake valve) either sequentially or in groups of cylinders such as one bank of a V-8 per injection event. These systems are designed to operate at or near stoichiometric mixtures. One promising technique to meet 1977 emission standards is to operate at stoichiometric with feedback control (using a $O_2$ sensor in the exhaust manifold) and employ a 3 mode catalyst for simultaneous reduction of HC, CO and NOx emissions. Bendix appears to be well advanced in the technology of this concept.

Some of the interesting features claimed for a fuel injection system are:

- Cylinder to Cylinder fuel distribution is better than with carburetor - EFI allows leaner overall operation without misfire than possible with normal carburetor.
- Less enrichment required for acceleration performance because fuel is delivered where needed - no distribution problem or transport delay.
- Enrichment during warm-up can be scheduled to reduce emissions and fuel consumption.
- Fuel cut-off during deceleration is used to reduce overall fuel consumption and emissions.

Bendix could not supply a complete set of engine map data to compare against a baseline case with carbureted engine. Claimed that all data belongs to customers and is proprietary. Only data available was that contained in the references below. This was not complete enough for use in computer simulation studies. We estimate a 5-8% improvement could be available from EFI.

## FIELD TRIP REPORT

**COMPANY VISITED** DATE 10-12-73

Ethyl Corp. Research Laboratories
W. 8-Mile Road
Ferndale, Michigan

Telephone: 313-564-6940

**PERSONS SEEN**

Mr. Harold Gibson, Manager
Mr. Dan Hirschler, Dir. Autom. Research
Mr. Wm. Adams - Research Advisor

**SUBJECT:** The Ethyl Corp. "Lean Reactor" system - Fuel Economy and Emissions Characteristics.

**GENERAL CONCLUSIONS**

The Ethyl Lean Reactor system comes close to meeting the 1975 Federal exhaust emissions standards and simultaneously shows a 10-15% improvement in fuel mileage over a 1973 production car. Other published results on the Ethyl system suggest about 0-5% economy improvement over 1973 model cars. No engine map data was available on this system for use in computer simulation.

**SUMMARY OF INFORMATION OBTAINED**

Ethyl Corp. has worked on the development of a Lean Reactor System for exhaust emission control. This system is described in references 69, 70, 71, and 75. It features a high velocity 3 barrel carburetor which provides excellent fuel atomization and mixing under all operating conditions, thereby promoting uniformity of fuel distribution and providing good driveability at lean mixture ratios. Air/fuel ratios as high as 18 or 19:1 can be used without EGR but when EGR is required for NOx control A/F is reduced to 17.5:1. A major feature of the carburetor is the combination of one small plain-tube carburetor venturi for light load operation with two variable venturi secondary barrels for higher power operation. Other features of the overall system include (1) a modulating EGR system permitting the amount of EGR to be tailored to different driving conditions, (2) design modifications for fast carburetor warm-up, and more rapid carburetor air preheat, (3) stainless steel tube inserts in the exhaust ports to retain exhaust heat for the manifold reactor and (4) larger, well insulated exhaust manifold reactor to burn out HC and Co. and (5) ignition timing control system modified to give best balance among emissions, economy and driveability.

These lean reactor modifications applied to experimental cars have reduced emissions to within the proposed California levels for 1975-76 but are not quite sufficient to meet 1975-76 Federal Standards. This excellent emissions performance is obtained with fuel economy equal to that of current 1973 model cars.

Complete engine fuel maps were not available for this lean reactor system. Most Ethyl lean burning test data has been taken on cars (not engine dynamometer) and driveability was emphasized strongly. Only data available is road test data. Much of this type data on emissions and fuel economy is given in reference 70. However, the latest road test data available from Ethyl is tabulated below. It shows that the lean reactor system which nearly meets 1975 Federal emissions provides 10% increase in MPG over the Federal driving cycle and about 15% increase in MPG over city and city/country routes as compared with the 1973 model reference car. The fuel economy is nearly as good as the 1971 reference car.

Lean Reactor Car No. 775

| | 1975 CVS Emissions g/mile | | | | | Fuel Economy, MPG | |
|---|---|---|---|---|---|---|---|
| | HC | Co | NOx | 1972 CVS | 1975 CVS | City Route | City-Country Route |
| Ethyl Data prior to EPA Test | .66 | 5.0 | 1.31 | 9.96 | 10.5 | 11.6 | 16.2 |
| EPA Test Data, May, 1972 | .81 | 5.74 | 1.38 | 11.23 | 11.41 | - | - |
| Current Ethyl data | .61 | 5.3 | 1.48 | 10.0 | 10.7 | 12.0 | 16.3 |
| Ethyl data on Prod. 360 Plymouths | | | | | | | |
| 1971 Model | - | - | - | 11.1 | 11.8 | 11.1 | 16.7 |
| 1973 Model | - | - | - | 9.06 | 9.69 | 10.25 | 14.1 |

Notes: Fuel economy based on weighed fuel except tests at EPA, which were carbon balance.

## APPENDIX II

### Responses from Industry to Findings of this Study

The following letters were received from industry after reviewing the preliminary draft of this report. The responses were taken into careful consideration and incorporated wherever possible in the final draft of the report.

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# COMMENTS ON ADL REPORT BY GENERAL MOTORS

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# A Study of Technological Improvements in Automobile Fuel Economy
February, 1974

## INTRODUCTION

Overall this report reflects an effort on the part of the authors to understand the variables and to objectively assess them. Their stated objectives were:

### The Primary Objective

1. Provide some insight into the factors which affect fuel consumption in the passenger automobile.

2. Identify and evaluate the individual technological improvements which are available in the near term for possible incorporation into a vehicle design which will reduce the fuel consumption level of the 1973 passenger automobile by 30%.

The Secondary Objective was to provide a source of data for both the Department of Transportation (DOT) and the Environmental Protection Agency (EPA) for use in advising governmental officials on regulatory and policy matters related to minimizing passenger automobile fuel consumption.

The Third Objective was to provide preliminary guidelines to be used by DOT/EPA in preparing plans for a possible validation test of a synthesized vehicle design recommended as a result of this study.

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Note:

We have not addressed the subject of cost. At this time we don't have sufficient information to do an effective cost analysis. We feel that A. D. Little also had insufficient information in this area.

## OVERALL CONCLUSIONS

1. A reasonable cause-effect relationship has been used. The panel has apparently tried to use attainable economy effects for the various factors considered.

2. The panel acknowledged that emission performance cannot be predicted. We agree. Emission standards and attainable emissions are critical to this study and its economy conclusions.

3. The ability to incorporate the economy factors considered in production vehicles in the time frame considered is questionable, some timetables are very optimistic, cost effectiveness of these changes and the time frame must be examined. Invention is required on some factors particularly the continuously variable transmission.

4. The passenger car diesel potential is overstated. The BTU/gal content of the fuel, the performance effect and the particulates problem will reduce the economy advantage.

## SCOPE AND CONDITIONS OF THE STUDY

Two 1973 vehicles were chosen, a standard size car at 3800 to 4200 pounds, and a compact size car at 2750 to 3200 pounds. The referenced vehicles were considered by preference of engine size, type, body style, optional equipment such as power steering and air-conditioning. The fuel consumption evaluation used a driving cycle which was made up of the EPA emission test and road load speeds from 30 to 80. This driving profile allocates 33% of the mileage to the EPA emission schedule and 67% distributed over the constant speeds. This driving schedule may at first appear to be naive but it shouldn't represent a major error as far as predicting the effect of changes.

The study group obtained their data by talking with manufacturers and examining literature on the subject. Their work represented a paper study only and they emphasize that final evaluation of these effects must be obtained by running hardware.

After looking at the various ways of improving economy, they combine what they consider the most promising factors that showed improved fuel economy. They then ranked these designs with an evolutionary time frame.

## Qualifiers

Several qualifiers to the overall approach were and need to be applied. They have one at the bottom of Page 7 which says, "Actually we feel that building and testing proposed vehicle models is the only way to validate the overall emission, fuel consumption projections."

Other qualifiers were brought out at a briefing on the Arthur D. Little report in Washington on July 10, 1974. This briefing was attended by Craig Marks, Ernie Starkman, Fred Bowditch and Chuck Amann. There were several comments made concerning the work at that time. First, it was indicated that the changes shown were not necessarily going to guarantee a car that would meet the required emission standards. This qualification was confirmed in a later discussion with Cline Frasier of DOT, and it was pointed out that the Arthur D. Little report has reached the conclusion that there is no way at the present time to predict the influence of any of the proposed changes on exhaust emissions.

There was quite a bit of emphasis on the lightweight diesel engine and Charles Amann pointed out there were particulate problems associated with this engine and other problems that were not properly covered in the report.

## Discussion

Fifteen specific factors were looked at that could be used to improve fuel economy. These are included in a large summary chart incorporated in the executive summary and the main report. The chart includes estimates of the change, the time frame, and the change in fuel consumption. A detailed discussion of each of these items follows:

## INDIVIDUAL ITEM DISCUSSION

### 1. 10% Reduction in Frontal Area

It was predicted that this change in frontal area would yield a 1.2% reduction in fuel consumption for the full size car and 1.97% reduction for the compact car. We have calculated data that shows a 5% reduction in fuel consumption on the Highway and Interstate 55 schedules for a 4000 pound automobile with a 10% change in frontal area. Considering that the A.D. Little estimate uses a weighting of the EPA schedule and the constant speed tests, their estimate of the effect looks reasonable.

A 10% reduction in area would have to occur primarily in width since the height cannot be reduced without affecting seating comfort, ease of entry, or structure. Width is one of the basic differences between the medium, intermediate and big car lines at 72.4 for the Nova, 76.6 for the Chevelle, and 79.5 for the Chevrolet for 1974. Reducing the width 7 to 8 inches is severe. Ten percent over the whole car line appears overly optimistic.

### 2. 20% Reduction in Drag Coefficient

The estimated changes are double the estimated change in fuel consumption for the 10% reduction in frontal area, and this would be consistent with our data. The percent reduction for the standard car is 2.4 and for the compact car 3.96. We would predict about 10% change in fuel consumption on a 4000 pound car with that change in coefficient of drag on the Highway or Interstate 55 with no effect at the low speed EPA schedule. Weighting of these schedules would then make the estimated changes the A. D. Little group predicted as reasonable.

It is important for both items 1. and 2. to question the ease of obtaining the shape changes. "Simple" styling changes to achieve a reduction in drag coefficient as indicated in the writeup run tremendous risks in the marketplace. Unacceptable appearance can lose automobile sales and defining acceptable is difficult. Radical revisions are usually accomplished progressively during several basic model changes and this would require many years.

3. 10% Weight Reduction

This amounts to a 300 pound reduction on the compact car and a 400 pound reduction on the full size car. They have applied a factor of about 7 gallons decrease in fuel consumption per hundred pounds per 10,000 miles for their weight change. This appears to be a reasonable number based on the earlier studies at Engineering Staff when the performance of the vehicle was allowed to increase as the weight was reduced. If the performance was maintained as the weight was reduced with a smaller engine, and this might not be possible for small changes in weight considering presently tooled engines, we would predict a larger effect of the weight change. It appears that the A. D. Little group has been realistic and conservative with their estimate of the weight effect assuming the gain can be obtained.

HSLA steels are not of value except in areas where strength rather than stiffness is required. We have not seen corrosion resistance claims greater than for plain carbon steel. The aluminum projections are interesting. Problems of repair, dent resistance, assembly and corrosion compatibility need answers. The assumed weight changes may be somewhat optimistic based on the above considerations.

4. Radial Tires

The program predicts a 2.3% reduction in fuel consumption for the full size car and a 3.3% reduction in fuel consumption for the compact car. Proving Ground data, from a memo of January 19, 1974, showed an average of 4 to 7% economy improvement with radial tires on the Suburban, Highway, Interstate, and Constant Speed 30, 50, 70 schedules for three different automobiles. Essentially no change was observed in the Central Business District. It would appear that the A. D. Little estimates of change for the radial tire are realistic and possibly conservative.

5. Total of Items 1. through 4.

The study group has merely added the percent reductions in fuel consumption for the first four items and came up with an 8.4% reduction for the full size car and a 12.4% reduction for the compact car. These reductions do not appear to be out of line considering the assumptions. However, the attainment of some of these assumptions is questioned even with major body changes.

6. Standard Engine with Optimized Spark Setting, Improved Carburetor and Catalytic Converter

The group has predicted a 6.8% reduction in fuel consumption for the full size car and 6.8% for the compact. This is contrasted to our prediction of 13% improvement in fuel economy for the 1975 Federal car compared to the 1974 Federal car. Based on these emission standards, their prediction would appear to be conservative. However, looking at the standards of .41, 3.4, and 2.0 which is also considered in the A. D. Little report, the predictions may be optimistic. We have not demonstrated a capability of meeting .41, 3.4, and 2.0 standards with the standard engine and catalytic converter yet for 50,000 miles. Attempting to meet these standards with that system may lose miles per gallon back to the 1973 level and possibly even more.

7. Lean Burn Engine with Improved Carburetor or Electronic Fuel Injection, Thermal Exhaust Reactor, Modulating EGR, Optimized Ignition System, and Possible Catalytic Converter

This sytem has been assigned a 6.8% reduction in fuel consumption over the 1973 car. The same discussion used with item 6. applies. The change in standards from 1975 Federal to the .41, 3.4, and 2.0 level could well make the difference in fuel economy on this system.

This approach simply involves operating an engine leaner than stoichiometric, and supposedly at the best economy air-fuel ratio. While theoretically the thermal efficiency of an I.C. engine should continue to increase with increasing air-fuel ratio, as a practical matter the deteriorating quality of combustion ultimately causes a decrease in efficiency. With the best mixture distribution and charge preparation practicable, the best economy air-fuel ratios are 17/1 to 19/1 at best economy spark advance, and approximately 16/1 when the spark is retarded. This latter point is especially important for two reasons:

(a) At 19/1 and best economy spark, the NOx emissions are still too high to meet a 2 gm/mile standard without EGR. Driveability at 19/1 with EGR is unacceptable.

(b) The exhaust temperature (which decreases with increasing air-fuel ratio) is too low at best economy spark to permit post-engine HC oxidation in a thermal reactor. Since CO is low on the lean side, there are insufficient combustibles in the exhaust to maintain the minimum oxidation temperature. This temperature must be maintained by the sensible exhaust heat, and the spark retarded to achieve the necessary exhaust gas temperature. The "lean-burn engine," therefore, is actually operated leaner than its best economy point for emission reasons. While we concur that a lean-burn engine alone can meet the interim 1975 Federal Emission Standards at low mileage with acceptable fuel economy, it cannot meet standards of .41, 3.4, and 2.0 in an acceptable form without catalytic after treatment.

As to compression ratio increase, the octane requirement is determined at full load. If the lean-burn is to have normal performance, it must be returned to maximum power mixtures (approximately 13/1) at wide open throttle. The octane requirement (and allowable compression ratio) would therefore be no different than a "conventional" engine. Other alternatives would be to operate the engine lean at all times, either accepting the performance loss (approximately 50 percent) or to increase the displacement of the engine. The latter choice would probably negate any fuel economy gain from an increased compression ratio.

### 8. Closed Loop Exhaust Emission Control Systems, Stoichiometric Air-Fuel Ratio, and Optimized Ignition System

A 9% reduction in fuel consumption is predicted for the full size car and the compact with this system. This system could give the same improvement assigned to items 6. and 7. based on the 1975 Federal Standards and using a catalytic converter. It would suffer the same peralty when considering .41, 3.4, and 2.0 standards.

Since this sytem by definition operates at the stoichiometric air-fuel ratio (approximately 14.7/1), there is actually a slight (and insignificant) fuel economy loss from an engine operating at its best economy air-fuel ratio. However, because at least a portion of the NOx emission control is to be accomplished through catalytic reduction, the engine-out NOx can be higher than with other systems at the same NOx standard. Since NOx is a product of efficient (high temperature, high pressure) combustion, fuel economy is better at higher engine-out NOx levels.

The "10 to 20%" fuel economy improvement requires some perspective, however. General Motors work to date shows no change from comparable 1975 model vehicles, although at lower emission levels. Since the data show the 1975 model fuel economy to be improved from the 1974 models approximately 13 percent, the statement may be valid if the 1974 models are used as a baseline or the 1973 models selected by A. D. Little. A more accurate way to portray the picture, however, would be to state that the oxidation catalyst (be it 1975 model or 3-way) permits carburetor and spark calibrations resulting in better fuel economy and the reducing catalyst permits a lower NOx tailpipe emission without additional sacrifice of economy.

Catalyst durability is a current and continuing problem with this approach, with loss of reducing capability occurring in less than 4000 miles.

## 9. Turbocharged Spark Ignition Engine

A. D. Little does not recommend this system.

## 10. Stratified Engine, Open Chamber Type Only - May Require Catalytic Converter

The report assigns a 15% fuel consumption reduction for this approach. The A. D. Little report did not consider prechamber stratified charge engines because of no evidence of a fuel economy improvement. Our data, and those in the public domain, are in agreement with that position.

The report does, however, consider the direct chamber ignition stratified charge engine of the Texaco TCCS and Ford PROCO type. The claimed advantage of this approach are twofold:

(a) Increased efficiency due to the elimination of throttling and the inlet pumping loop (all load control is ideally by fuel control, as in a diesel); and

(b) Higher allowable compression ratios due to reduced octane requirements.

It should be noted that both of the above are apparently true in the absence of emission requirements 1/; however,

(a) Intake throttling at idle and low airflows are necessary for HC control;

(b) Unburned HC emissions from the engine are inherently high (apparently due to lack of ability to maintain stratification), and require catalytic after treatment to meet present emission standards.

In addition, the direct cylinder injection equipment is complex and costly.

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1/ Presentations by D. Plungis (EPA) and D. Raggio (U.S. Army Tank Automotive Program); NATO Symposium on Low Pollution Power Systems Development, October 1972

However, the combustion during injection feature of this approach does avoid the high rates of pressure rise and flame front velocities (and therefore the tendency to knock) of the conventional Otto cycle engine, and therefore permits higher compression ratios for the same octane requirement.

This combustion process, therefore, approaches that of the diesel engine, but without the benefit of the higher heating value fuel, and with the disadvantage of the increased volatility fuel making stratification more difficult.

The final statement regarding the availability of the Honda concept before 1982, and its lack of applicability to larger (V-8) engines is simply not true in light of both GM and public data, and Honda's introduction of CVCC vehicles in Japan in 1973.

## 11. Lightweight Diesel Engine

The report assigns a 16.2% reduction in fuel consumption for the full size car and 20% for the compact car.

Two errors here are worthy of note:

(a) The diesel engine is not "widely" used in Europe. Only a small percentage of passenger cars sold annually are diesels.

(b) The prechamber diesel engine, used in passenger cars to avoid the high rates of pressure rise (diesel knock), reduces the economy potential of the direct injection diesel process.

In fact, any theoretical analysis will show that for the same heat release per cycle, the Otto cycle achieves better efficiency than the diesel cycle, albeit by virtue of developing higher combustion temperatures and pressures.

The attraction (if any) of the diesel engine is:

(a) The direct injection during combustion minimizes wall-wetting and quench film, a source of HC and CO;

(b) The lower pressures and temperatures result in lower NOx emissions;

(c) The lower volatility (diffusivity) of diesel fuel compared to gasoline makes stratification easier to maintain than in the PROCO or TCCS process.

## 12. 4-Speed Automatic Transmission with Optimized Shift Logic and Lock-Up Torque Converter

Reductions of 9% in fuel consumption for the standard and 13% for the compact size car are indicated for this concept. Recent calculations for a GM "A" body with a 350 CID V-8 indicate a 10.7+% reduction based on the A. D. Little weighting of the FDC-CVS-72 mpg and constant speed mpg. The A. D. Little values appear reasonable for a fully locked clutch since the standard car is somewhat heavier than our intermediate car. The compact car gain may be slightly optimistic even though the base car had a two speed automatic transmission and a larger axle ratio. However, GM experience indicates that a fully locked clutch may not be acceptable from a driveability standpoint. Any clutch slippage will result in a smaller reduction in fuel consumption.

The time frame of 1976-77 can probably be achieved only in part of the car lines. Lock-up converters can occur in all car lines much before the 4-speed gear box since economical integration of the fourth gear often requires substantial changes in design and tooling. Typical current transmissions will probably need to be about 3 inches longer and weigh a minimum of 10% more. A. D. Little indicates the transmissions would be slightly larger and 5-10% heavier.

This all assumes that driveability and emission requirements are met. GM studies show that the converter clutch must be used in all gears to obtain the maximum economy benefits. Driveability is seriously affected when this is done. The above good gains can be obtained with the clutch limited to the top three gears but even here driveability is a problem and driveline torsionals are part of the problem.

In summary, this concept may not be as low in risk and as well within the state-of-the-art as A. D. Little indicates. Shift schedules suitable for emissions control and driveability may result in less than the indicated economy gains, particularly under the FDC emissions schedule and similar driving conditions.

The report also considered the manual transmission but concluded that it did not provide the same convenience as the automatic and would not be acceptable to the customer. We agree to this. The conclusion that the net effect of the converter lock-up device would be the same as the manual transmission is not exactly true. The automatic transmission hydraulic system pump operates continuously. The spin losses in the gear set tend to be higher than those in the manuals. The net result is a higher parasitic loss with the automatic transmission. The differences are minor in comparison to other potential gains. It is difficult to reduce these losses much below the present status of the highly developed automatics.

## Improved Engine and Transmission Matching

The report discusses transmission changes under this heading. A. D. Little recommends two transmission concepts as items 12. and 13. in the Table.

The benefits of improved engine and transmission matching can come from two distinct sources: (1) Improved efficiency within the transmission system and (2) operation of the engine at lower BSFC conditions.

The 4-speed automatic with torque converter and lock-out device attacks both of these areas. The lock-out device improves the efficiency of the transmission system by substantially eliminating the torque converter losses during lock-out. The addition of the fourth gear increases the ratio coverage of the transmission which allows a reduction in the driveline ratio (N/V) in top gear (fourth). This increases the torque load and reduces the speed of the engine resulting in better BSFC conditions. The lock-out (or slip limiting) device is mandatory, particularly in top gear, to prevent increased losses in the torque converter resulting from the increase in torque and lower speed with the lower N/V.

## 13. Continuously Variable Transmission (CVT) and Heavy Duty Engine

Reductions of 12.2% and 20% in fuel consumption for the standard and compact size cars, respectively, are shown by A. D. Little. GM experience with toric drives in intermediate size cars showed no gain on schedules and at 70 mph. Gains of 30% occurred at 30 mph. When the controls for this transmission were calibrated for satisfactory performance, driveability, and engine speed (noise level) the economy was lower. Considering the amount of past development the A. D. Little assessment is probably optimistic.

While the chart (Table 4-38 of the main report) does not differentiate, there are two distinct concepts suggested by A. D. Little as approaches to the CVT lumped into the item 13. tabulation. While these concepts share certain common problems and philosophies they also have some distinctly different problems.

The key questions remaining are:

(a) Can predicted efficiencies be achieved in the power ranges required in the base cars?

(b) Can the noise, control, manufacturing cost, durability and dependability problems be solved at the costs estimated?

Demonstratable car systems are still not available to answer these questions. Even the basic traction drive efficiency maps in the sizes needed are not generally available. We don't see this concept as a viable approach at this time since invention is required.

14. Constant Speed Drive for Accessories without Air-Conditioning

The report assigns a .95% reduction in fuel consumption to this concept for both the standard and compact sized vehicles. They conclude it is not cost effective and state that they will not consider it further.

The constant speed drive as proposed in the report would probably cause a loss in fuel economy on schedule driving because of the necessity of running the accessories fast enough at low car speeds to satisfy accessory requirements at high car speed (i.e., the engine water pump). However, a well designed, inexpensive 2-speed accessory drive would probably give fuel savings in the range predicted by the report (about 1% total fuel savings for both full size and compact vehicles).

15. Constant Speed Drive ..... with Air-Conditioning at 1/3 Duty Cycle

The report predicts a 2.9% reduction in fuel consumption for this concept. It is applied to standard size cars only in the report. This item is shown as "probably not cost effective if much over $25-50, and if air-conditioning runs on light duty cycle, will not consider further." We agree that the estimated 2.9% fuel consumption reduction is reasonable.

If a 2-speed accessory drive were used in place of the proposed constant speed drive, GPSIM schedule fuel economy results on a weighting of GM schedules predict the following fuel consumption reductions with air-conditioning in operation:

B Car - .9%
A Car - 2.0%
X Car - 2.9%
H Car - 4.8%

The resulting "duty cycle" of the compressor would be about 2/3 as the term is defined in the A. D. Little report. The use of other means of reducing the "duty cycle" such as cycling clutch, inside evaporator, reduced compressor size, etc. should reduce fuel consumption by an additional 2%.

COMMENTS ON ADL REPORT BY FORD MOTOR CO.

August 16, 1974

# Preliminary Comments on Arthur D. Little Inc. Report Under DOT Contract No. DOT-TSC-627

## "A Study of Technological Improvements in Automobile Fuel Consumption"

It is agreed that most conclusions require further validation and substantiation as ADL recommended in their report.

The staff of ADL recognizes the lack of uniform test methods and standards for determining fuel consumption within the industry and Government.

They realized that it is very difficult to obtain useful experimental data to serve as guidelines in establishing simulation method and simulation baseline, or to validate the simulation method being developed.

They also pointed out that their simulation technique is merely a tool and does not replace the need for experimental testing and engineering evaluation programs for comparison purposes.

The fuel economy simulation computer program adopted for this study was developed by Scientific Energy System Corp. (a sub-contractor on this project). This fuel economy computer program is over-simplified as compared with Ford and GM simulation programs. In its simplicity, it has neither the capability to predict the interactions between emission control and fuel economy nor the capability to predict the interactions between engine wide open throttle performance and fuel economy. This computer program cannot accept automatic transmission shift patterns as functions of engine manifold vacuum and driveshaft speed. Further, it cannot accept gear box and axle efficiencies as functions of load and speed through the operating ranges.

Practical reductions of vehicle weight, rolling resistance, aerodynamic drag, axle ratio and accessory loads usually result in fuel economy improvements in the range of up to 10%. Thus, the current simulation method adopted may not be sufficiently sensitive to evaluate these changes.

The EPA emissions test route (CVS Route) and 20, 30, 40, 50, 60, and 70 mph steady speed fuel consumption data are adopted as fuel economy measurement criteria. Only the steady speed test data are used directly to compare with simulated data.

The EPA-CVS route is a legitimate test route for emissions analysis but it cannot be treated as a typical American City fuel economy route according to Fuel Economy Measurement Procedures Task Force of the SAE Technical Board. The ADL fuel economy test results obtained from this route should not be compared directly with

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those of automotive manufacturers.

Proprietary engineering data and financial data are not included in this study. These pertinent data must be considered before making any important fuel economy decisions.

The costs of engine and transmission should be listed separately to allow the evaluation of the cost effectiveness of each fuel economy component improvement and for easier estimation of the total vehicle price increase associated with each fuel economy gain.

The cost of a four-speed automatic transmission with a torque converter equipped with a lock-up device is not minimal as suggested.

We agree with ADL that automatic four-speed transmission with torque converter lock-up is a near term 1976-1979 fuel economy improvement possibility.

We further agree with ADL that continuously variable transmission may be implemented in the early 1980's.

The investigation and discussion should be expanded to consider the interactions of spark retard, exhaust gas recirculation (EGR), fuel octane requirements and catalyst application rather than only adjusting air fuel ratio for improvement of the vehicle fuel economy.

The investigation and discussion should include the optimization of fuel economy of the current production engine with moderately lean A/F ratios and a catalyst. The suggested improvements should be specified.

Discussion of the lean-burn engine concept should cover the fuel octane requirement, combustion rate, EGR and spark controls. The suggested 19:1 A/F is very lean and may not be practical for driveability reasons. Many of our production engines run at 10% lean from stoichiometric A/F ratio in many modes in order to control HC, CO emissions.

This report should categorize the cost and fuel saving with each proposed emission standards.

Many diesel engine technical problems of long standing such as noise, smoke, odor, particulate emission and excessive weight are assumed solvable in reasonable time and at reasonable cost and without severe loss in economy or performance. These assumptions may be overly optimistic.

In addition the design, development, and tooling costs for conversion to diesel are heavy investments which cannot be considered lightly. The bottle neck of machine tool delivery for conversion of production line must be studied.

A 10% weight reduction is not easily achieved, especially with recent weight increases in production passenger cars due to emission control systems and safety requirements. On the other hand, a drastic reduction in vehicle weight, frontal area and air drag requires new design, development, and tooling with greatly added costs which may create buyer resistance.

In conclusion, the evidence presented in this study is insufficient to establish that any of the suggested powertrains for 1980 mass production will be able to meet the specified emission constraints and provide 30% improvement in fuel consumption.

TEXACO
PETROLEUM PRODUCTS

AUTOMOTIVE ENGINE
DEVELOPMENTS
WILLIAM T. TIERNEY
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July 10, 1974

Mr. Herbert H. Gould/TMP
DOT/Transportation Systems Center
Kendall Square
Cambridge, Massachusetts 02142

Dear Herb:

As requested in Mr. C. W. Frasier's letter to me of June 20, we have reviewed the Arthur D. Little report draft of "A Study of Technological Improvements in Automotive Fuel Consumption." We wish to offer the following comments on the section dealing with Stratified Charge Engines, and the section entitled Special Considerations - Impact on Fuel Supplies and the Automotive Industry.

Stratified Charge Engines

1. Page 14, fourth paragraph in Executive Summary, and Page 193, third paragraph in main report. Change Texaco Company to our official name Texaco Inc.

2. Page 105, first paragraph in main report. Texaco reference 31 is in error.

3. Page 107, second paragraph. Statement implies that we did not supply engine map on TCCS which was given in 1968 SAE Paper No. 680042. Copy is attached for your use.

4. Page 105, last paragraph and Page 109, first paragraph. To our knowledge, the TCCS is the only stratified charge engine that has a truly multifuel capability. At any rate, the same degree of fuel tolerance cannot be assigned to all stratified charge engines.

5. Page 108, Figure 4-21. Air swirl is in wrong direction. It should be clockwise.

6. Basically, the report lumps all stratified charge engines together which we think is unfortunate and creates a misleading impression. All stratified charge engine concepts are not at the same stage of development; all are not truly multifuel as stated above; all do not operate with a lean premixed charge (TCCS does not); all do not have the same mechanical limitations, such as with dual intake valves and dual carburetion; all do not have the same durability problems; all do not have problems in maintaining driveability (we presented SAE Paper No. 740563 on May 14, 1974, copy attached, which shows that TCCS driveability and durability were maintained for 50,000 miles).

7. We would take issue with your general classification of stratified charge engines as high risk. At this stage of development of TCCS, we would not consider the risk level as high as other stratified charge engines, nor would we consider the risk level any higher than other concepts such as closed-loop stoichiometric fuel control which you classified as low to medium risk level.

8. We suggest that you expand the section on stratified charge engines and point out the various combustion concepts, the current stage of development of each, emphasizing the emission levels and fuel economies available and the impact of each design on our petroleum energy supplies.

## Special Considerations - Impact on Fuel Supplies and the Automotive Industry

1. Shifting of gasoline boiling range fractions into diesel fuel can be practiced to some extent to increase diesel avails at the expense of gasoline. Such a shift would be limited by cetane number, 10% point, and flash point of the diesel fraction. A change in blending practices would occur only if significant changes in diesel fuel volume relative to gasoline occurred. With this situation, the diesel fuel would contain greater proportions of cracked components than at present as a result of maximizing diesel fuel yield. This would aggravate the cetane number problem.

2. Another problem that is not clearly recognized in the write-up is the fact that converting material boiling above the diesel fraction to diesel fraction inevitably results in the production of gasoline boiling range material. Thus, the gasoline boiling range pool consists of virgin material in the crude plus that material produced by conversion of heavy material to diesel, and

plus that material produced by volatility balance processes such as alkylation and polymerization; less the gasoline material that can be blended into kerosene and diesel fuel, and less yield losses from reforming, etc. The gasoline pool will be a significant volume even when operating all out for maximum diesel fuel.

3. Adequate recognition is not given to other problems of diesel fuel usage. Cetane number is just one problem. Sulfur content, as well as cloud and pour point problems are also very important. Diesel engine cold starting during winter months would present problems. A diesel fuel that has high cetane for good low temperature running would inherently be high in pour and cloud, resulting in cold weather operational problems. Some of the best low sulfur fuels are 0.2 to 0.3% (vol.) sulfur, while gasoline is at least an order of magnitude less. This would increase sulfur dioxide, sulfate emissions markedly. Thus, the problem is not as simple as the write-up implies.

4. Nothing is said in the write-up of the advantages of a multifuel engine such as the TCCS engine in regard to its impact on fuel supplies. Such an engine, which has no octane or cetane requirements would allow the refiner to really optimize energy production.

Mr. Frasier's letter did not request that the report draft be returned to you. Hence, we will retain it in our files unless you advise me otherwise. It will not be distributed or discussed outside of the group that contributed to the foregoing editorial comments.

We appreciate having had the opportunity to review the report draft. If you wish to discuss any of our comments further, please do not hesitate to contact me.

Very truly yours,

W. T. Tierney

RJP-cf

Attachments

**Tracor Sciences & Systems**

Tracor, Inc
6500 Tracor Lane
Austin, Texas 78721
Telephone 512 926 2800

11 July 1974

JHK-74-7-1

Mr. Herbert H. Gould
Department of Transportation
Transportation Systems Center
55 Broadway
Cambridge, Massachusetts 02142

Dear Mr. Gould:

As requested by Mr. Cline Frasier in his letter of 20 June, we are enclosing our comments to the sections pertaining to continuously variable transmissions and constant speed accessory drives of "A Study of Technological Improvements in Automotive Fuel Consumption" by Arthur D. Little Inc.

Over all, we feel this is a fine report. The overestimated cost and complexity of implementing a continuously variable transmission and a constant speed accessory drive, and the concern of associated development risk appears to be due to a lack of in-depth understanding of these drives not possible for a report of this size.

Sincerely,

James H Kraus

James H. Kraus
Project Engineer

JHK:ec

Enclosure

# COMMENTS ON CONTINUOUSLY VARIABLE TRANSMISSION

## VOLUME I: EXECUTIVE SUMMARY

### 5.1.3.4 Technological Risks

High - Neither durability nor maintainability are expected to be a risk area with the Tracor CVT.

### 5.1.3.4 Customer Acceptance

Medium Acceptance - The Traction CVT will reduce noise for normal operation by suppressing engine RPM and accessory RPM. The Transmission per se is very quiet, like a well adjusted ball bearing. Noise during wide open throttle for full acceleration may be greater due to increased engine RPM, but under this unique condition (which is driver controlled) we believe added noise is acceptable.

## VOLUME II: MAIN VOLUME

### 4.3.4.10.2 Problem Areas

A. The automotive engine will, indeed, be subject to a higher load factor, because it will be required to produce equivalent power at a reduced RPM. Optimum fuel economy will probably occur with about 2/3 to 3/4 throttle opening. We doubt, however, that the engines would "require a complete redesign." A nominal degree of hardening could be accomplished with a relative increase of the water pump speed.

B. Engine noise will indeed increase during W.O.T. operation; however, it will be significantly reduced during normal driving because of reduced engine and accessory speeds. We have generally found that motorists do not object to noise during W.O.T.

C. The continuing changing ratio aids the life in a Traction CVT by spreading the fatigue stresses over the Traction discs.

D. Controls do indeed present a problem at present. The engine vacuum controls which worked well on the fleet of test cars at Curtiss-Wright can no longer be used as there is virtually no vacuum with E.G.R.

Controls of a three or four-speed automatic transmission are quite complex, and probably will get worse with the addition of torque converter lock-outs. When properly developed, we feel the controls for a CVT should be less complex than present automatics as the device is continuous.

## CHART OF CONDITIONS AND CONSTRAINTS

Initial cost of a CVT is estimated at $200 over present torque converter automatics. We believe this is much too high.

### References:

1. DOT Study of "Technological Improvements in Automotive Fuel Consumption" by Southwest Research Institute shows an estimated production cost of $150 over a three-speed manual transmission, and $60 to $150 less than present three-speed automatics.

2. EPA Study "Automotive Gas Turbine Optimization Study," APTD-1291 by AiResearch Mfg. of Arizona. This study shows an estimated transmission cost of $233 for a Traction CVT as opposed to $267 for a standard automatic.

### Chance for Success

This is considered high risk by Arthur D. Little, whereas Tracor believes the Traction CVT is technically mature with demonstrated ability of automotive power and life requirements.

### Complexity

Tracor believes the controls for a Traction CVT will be less complex than present automatics when adequately developed.

### Cooling

Higher engine loading should not reject more heat to the exhaust and cooling systems. Total power output will remain unchanged and engine/transmission efficiency will increase; therefore, rejected heat should be less. Equivalent heat rejection will occur at lower engine speeds, so a speedup of water pump and possibly the cooling fan may be required.

## COMMENTS ON CONSTANT SPEED ACCESSORY DRIVE

## VOLUME II: MAIN VOLUME

### 4.3.5.3.6 Page 151

The constant speed accessory drive should be used to power all engine accessories except the oil and water pumps which need to run at engine speed. The fan, alternator, air pump, power steering, air conditioning, and any accessory hydraulic pump (may be required for power boost brakes, etc., with engine vacuum gone) all have maximum or near maximum power requirements at idle. Thus, from Figure 4-33, overall accessory load with a CSD would be about 5.5 HP as opposed to 16 HP at 3,000 RPM, and 24 HP at 4,000 RPM.

This could mean equal auto performance with an engine of approximately 20 HP less. The accessory generated noise, especially the fan, would be greatly reduced for normal driving.

## CHART OF CONDITIONS AND CONSTRAINTS

### Initial Cost

Past work with TRW and Chrysler Corp. has shown that the initial cost of the individual accessories and the mounting cost of these accessories can be reduced by approximately $18 - $25. This is without including the newly required air pump and possible accessory hydraulic pump. Thus, when treating the accessory package as a system, it should be possible to build the accessory CSD for the amount saved. At most, the addition of a CSD should be less than $5.00.

### Chance for Success

Tracor already has an accessory CSD operating in the Pinto Test car. This is a proven unit. The risk is in the cost area. Can the individual accessories be reduced in cost (including mounting) sufficient to pay for the CSD.

## Customer Operating Consideration

The spool CSD is very quiet, like a well adjusted bearing. The reduced RPM of the accessories during normal driving should reduce overall noise.

## Remarks

From the figures quoted in the chart, the accessory CSD with air conditioning shows a net savings of $125 including the probably overestimated initial cost. This exceeds the net savings for each of the first four items listed.

Also, if the engine size is reduced to take advantage of the reduced power demand, overall fuel savings should be significantly greater.

## Durability and Maintainability

Tracor believes the Traction CVT is more than capable of being designed for present automotive power and life requirements. A 60 HP drive was tested at full rating in worst condition (full reduction) for over 2,100 hours with no difficulties. This greatly exceeds automotive requirements.

## Customer and Operating Considerations

The Tracor Traction CVT is essentially dead quiet in operation. For normal cruise, the engine and accessories will also be quieter due to reduced operating RPM. There may be increased noise at W.O.T. due to increased engine RPM, but this is of short duration and is driver controlled. Tracor does not believe W.O.T. noise is a significant problem.

ETHYL CORPORATION
RESEARCH AND DEVELOPMENT DEPARTMENT
RESEARCH LABORATORIES • 1600 WEST EIGHT MILE ROAD
FERNDALE, MICHIGAN 48220

July 12, 1974

Mr. Herbert H. Gould/TMP
DOT/Transportation Systems Center
Kendall Square
Cambridge, Ma 02142

Dear Mr. Gould,

We appreciate receiving the draft copy of the report, A Study of Technological Improvement in Automobile Fuel Consumption prepared for the U.S. Department of Transportation and U.S. Environmental Protection Agency. We have reviewed the report and find it to be a very comprehensive and worthwhile study. We do have a few comments that pertain to our system, the lean burn approach as presented in the report.

On page 90, the report correctly attributes a 15-20% improvement in fuel economy to our system as indicated from the data submitted. Therefore, we are puzzled that Table 4-16 lists a fuel economy improvement of "about 10%" for our system. Perhaps this is a typographical error.

We were disappointed to note that a final average gain in fuel economy of only 7.5% was assigned to the lean burn system, because our data indicates it would be larger than this. However, we can understand that our data is limited and the authors had to take other's comments into consideration and, in addition, may have wished to be conservative in their estimated gains. Of more concern to us than the absolute fuel economy gains is the relative gain when compared to the Stoichiometric Air/Fuel Ratio Engines Using Closed-Loop Self-Tuning Systems and Catalytic Converters. In the absence of actual data for the latter system, it was assigned a higher fuel economy gain (10%) than the lean burn system (7.5%). We believe that the lean burn system should have an advantage in fuel economy over the Stoichiometric-Catalyst engine because of the ability of the lean burn engine to incorporate a high compression engine burning higher octane number leaded fuels. As the authors have pointed out, this is an important factor in our fuel economy gains. We believe that the lean air-fuel ratio at which we operate does not result in a fuel economy loss relative to that obtained at stoichiometric air-fuel ratio. In addition, we feel we have the inherent advantage for the lead-tolerant system of being able to raise compression ratio and/or advance ignition timing and attain better fuel economy by using higher octane fuel.

Our preceding comments do not alter our belief that the report is a significant contribution in the effort to identify the factors and engine systems that can contribute to better fuel economy. Be assured that we are continuing our work on lean burn systems with the objective of obtaining the best possible fuel economy while attaining emissions levels required.

Thank you for the opportunity to review and comment on this report.

Sincerely,

W. E. Adams

W. E. Adams, Director
Automotive Research and Application

WEA:ew

cc: Mr. Cline W. Frasier
Donald A. Hurter

G. J. HUEBNER, JR.
DIRECTOR OF RESEARCH
PRODUCT PLANNING & DEVELOPMENT OFFICE

**CHRYSLER
CORPORATION**

August 22, 1974

Mr. Herbert H. Gould/TMP
DOT/Transportation Systems Center
Kendall Square
Cambridge, Massachusetts 02142

Dear Sir:

In response to Mr. Cline W. Frasier's request dated June 20, 1974, the following comments are submitted on the draft report by Arthur D. Little Inc., "A Study of Technological Improvements in Automobile Fuel Consumption."

On the overall basis, we are in close agreement with the contents of this draft report. We find it to be an accurate assessment and compilation of the state-of-the-art, the potential magnitude of fuel economy gains, and the pros and cons of the various approaches. (The report does not contain, however, any data, information, or opinions that have not been available within the industry.)

Comments are as follows:

1. Recovery of any initial cost penalty is considered on a 3-year and a 10-year basis for evaluating cost effectiveness. Emphasis should be placed on a 3-year yardstick since initial cost has the primary effect on the first buyer.

2. The Transportation Energy Panel (formed in 1972 to assess technology for reducing energy usage in transportation) did consider and comment on the effect of Federally mandated standards for emissions and safety.

3. The accessories and improved accessory drives are covered very well. Regarding flexible decambering fans, these kinds of fans are currently used on some of our cars. While they are less costly than the viscous drive, they do incur a cost penalty over the standard rigid fan.

4. The closed loop approach uses a sensor ($O_2$) to permit feedback control of the fuel/air mixture and a 3-way catalyst which can operate within the "window" near stoichiometric operation. Fuel economy is to be gained by optimizing the spark and maintaining this mixture at all driving modes. The gain in fuel economy by operating at stoichiometric

P. O. BOX 1118 DETROIT MICHIGAN 48231

4. depends on the alternate system used for comparison which in turn depends upon the degree of emissions control applied. For example, the discussions on the merits of the lean burn approach (7.5% improvement) and stoichiometric operation (20% improvement) seem incompatible.

5. The report indicates that the use of a continuously variable transmission will aggravate the problem of NOx control because of higher engine loading. This is not necessarily obvious since the mass emissions when providing a given power at lower engine speeds (higher loading) will depend on whether the emissions concentration or the mass flow changes faster. The effect may also be different during road load, accelerations, and transients. It is possible that when operating over the Federal drive cycle there will be times when the engine is operating at a better NOx point and some times when it is operating at a worse NOx point with a CVT than an engine with a conventional transmission. Additionally, available methods for controlling these emissions should be applicable. In conclusion, we do not see any clear evidence that NOx will be a problem with use of a CVT.

In a letter dated June 19, 1974 Mr. John C. Sawhill, Adminstrator, Federal Energy Adminstration requested Chrysler's comments on "A Voluntary Program For Improved Fuel Economy." Chrysler's comments were sent to Mr. Sawhill on July 31, 1974. They contain information and comments on the Hittman report and they also describe Chrysler's approach to the fuel economy problem. I am enclosing a copy of our July 31,1974 letter to Mr. Sawhill together with all its enclosures.

Very truly yours,

G. J. Huebner, Jr.
Director of Research

GJH:mg

Enclosure

**ORSHANSKY TRANSMISSION CORPORATION**

PETER HUNTLEY, *Vice-President*
18 Bellevue Road
Belmont • Massachusetts 02178
(617) 489-2419

June 29, 1974

Mr. Herbert H. Gould TMP
Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge, Mass. 02142

Dear Mr. Gould,

With reference to the draft copy of the Arthur D. Little report A Study of Technological Improvements in Automobile Fuel Consumption, we have the following comments.

1. The text on page 141 draws attention to Table 4-25 in which the continuously variable transmission (CVT) is compared with a conventional three-speed automatic transmission. The same 302 cu in 1971 Ford V8 is used for both cases. The text incorrectly assumes that both drivelines give the same acceleration performance. Actually our calculations showed that with the CVT, the time for 0-60 MPH wide-open-throttle acceleration was reduced from 12.5 to 11 seconds. The Table 4-25 has been extracted from our Report 404, a copy of which is enclosed. On pages I-4 and III-81 to III-84, the Report shows that as far as acceleration performance is concerned, the change from a conventional automatic transmission to a CVT is approximately equivalent to a 10% increase in engine displacement.

This approach has been explored to greater depth in SAE paper 740308 (copy enclosed). It is shown in Table 8 of the Paper that the following two drivelines give essentially identical wide-open-throttle acceleration performance:

a) 302 cu in 1971 Ford V8 and the four-range hydromechanical transmission

b) 351 cu in 1971 Ford V8 and the Select Shift and 11 1/4 inch torque convertor

The reduction in engine displacement without sacrifice of performance provides an important contribution to the total improvement in fuel economy brought about by the CVT for the standard size passenger car. Whereas, Table 4-25 of the ADL report shows a 19% improvement when comparing drivelines having the same engine, Table 9 of the SAE paper shows a 32% improvement when comparing drivelines which give the same acceleration performance. The latter result is more consistent with the figures quoted on page 141 of the ADL report.

I also enclose a copy of the computer print-out relating to the various simulations run for the SAE paper. They permit the behavior of the engine and transmission to be observed at one-second intervals during the fuel-economy driving cycles and at one-tenth-second intervals during the acceleration runs. Note that the CVT transmission efficiency is mostly found to be less than 90%.

2. On Table 4-38 line 13 of the ADL report, it is stated that improvement in fuel economy due to the CVT is realized primarily at constant speed driving and in suburban driving. Our results, mentioned above, show that the fuel economy improvement due to the CVT in city driving is almost asgood as the suburban case.

For the Federal Driving Cycle we have found the following:

| | (a) | (b) |
|---|---|---|
| Vehicle weight | 3370 lb | 3400 lb |
| Engine | 250 cu in | 250 cu in |
| Transmission | Torque Flite | 2-range hydro-mechanical |
| Fed. Dr. Cycle, mpg | 17.75 | 22.43 |
| 0-60 mph, w-o-t, seconds | 15.0 | 13.5 |

By "trading'in" the improvement in acceleration performance for additional gains in fuel-economy, we anticipate that the 26% improvement in mpg will be boosted to over 30%.

Some of the improvement found for the Federal Driving Cycle derives from the fact that the required input torque to the transmission when "Drive" is engaged and the vehicle is stationary, is higher for the torque convertor than for the hydromechanical transmission by a factor of three.

3.a Comments in the ADL report concerning necessary engine modifications for operation with the CVT are, in our view, excessively gloomy and pessimistic. As far as we are aware, no detailed study has yet been made of the nature and extent of these modifications. The pessimism is prompted by an understandable inclination to caution in the face of uncertainty, rather than by the specifics.

Some modifications will necessarily reduce engine efficiency; for example, increases in oil, air and water pump capacities may be expected. On the other hand, for operation with the CVT, the rated power output may be sacrificed in favor of improved low-speed efficiency; for example, by optimizing valve timing for low speed operation.

In our simulation calculations we avoid the region of the engine map where torque is high and the engine speed is very low, even though this entails some loss in fuel economy. (For the 302 engine, we also avoid the high HC region at low engine speed although this again compromises the BSFC) The resulting 25% to 30% improvement in fuel-economy is still good enough to be of interest. The logical development and introduction of the CVT will, most probably, not face up to the problem of a redesigned engine until reasonable acceptance has been established of the CVT with slightly-modified, existing engines. In the early phase, the operating schedule on the engine map will be deliberately chosen to yield less fuel-economy improvement than the potential maximum. We anticipate that with very minor modifications, an alteration in the engine duty cycle is permitted such as to yield, say, one half of the full potential of fuel-economy improvement. Thereafter, engine characteristics will evolve, year by year, to secure more and more of the entire potential improvement.

3.b Finally, as a matter of detail, it must be pointed out that the remark on Table 4-38, line 13, of the ADL report regarding the heat rejection rate is hardly consistent with the First Law. Since the engine with the CVT is to be operated at a speed at which it supplies a given level of power more efficiently than in the case with a conventional automatic transmission, the total heat rejection rate must be less.

Dr. Coons of Southwest Research has made the point in a private communication that the important change is the peak heat rejection rate during the cycle.

It is hoped that these comments are of some assistance; I would prefer them to be regarded as observations and not criticisms. I have appreciated reading ADL's very thorough and useful study.

Yours sincerely,

Peter Huntley

Peter Huntley
Vice President

PH/jmw

Enclosures

cc: M. Koplow
Dr. Malliaris
Prof. Heywood
} no enclosures

**ENVIRONMENTAL TECHNOLOGY** DRESSER
DIVISION DRESSER INDUSTRIES, INC.
1702 mcgaw / santa ana, california 92705 □ 714 / 540-2807

August 30, 1974

Mr. Herbert H. Gould
DOT/Transportation Systems Center
Kendall Square
Cambridge, Mass. 02142

Dear Mr. Gould:

We thank you for the opportunity to review the ADL report. As I mentioned to you in our phone conversation, we disagree with some of the findings, particularly, the section on lean burn.

Although the Dresserator has advantages at any air fuel ratio, our efforts have been concerned with its application to lean burn. The report states that lean burn results in poor driveability and requires high octane fuels. We find neither of these to be true. We achieve excellent driveability at air fuel ratios of 18-18.5/1 and excellent economy, usually 5-15% increased over the baseline car, even though we are operating at NOx levels in the range of 1.0-1.6 gm/mi. This is accomplished without EGR or air pumps, etc.

Typically on 4500# cars we run .8-1.0 gm/mi HC, 4.0-6.0 gm/mi CO, and 1.0-1.6 gm/mi NOx. Since we have 4-5% oxygen as the exhaust at temperature, we feel the HC can be reduced below 0.4 gm/mi and CO below 3.4 gm/mi by using enlarged exhaust manifolds. NOx and economy are unaffected.

The report also states that the only way lean limit can be extended to 20-22/1 is by fuel injection. We find this also to be untrue. We generally can extend lean limit without misfire to this range on all cars. This is accomplished by our excellent cylinder-to-cylinder distribution.

We feel that the Dresserator should be no more expensive than a normal carburetor and our preferred single plane manifold should be cheaper than the usual dual plane. Our exhaust manifolds (if used) would be slightly more expensive. The net result is essentially a cost trade-off resulting in excellent cost benefits.

Again, thank you for the opportunity of presenting these comments.

Sincerely,

Lester P. Berriman

Lester P. Berriman mp
Director of Engineering

LPB:mp

# APPENDIX III

## PERFORMANCE DATA ON INNOVATIVE DEVICES

1. Powerplants
2. Transmissions
3. Accessories

# APPENDIX III-1 -- Powerplants

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ETHYL CORPORATION
1600 WEST EIGHT MILE ROAD
FERNDALE, MICHIGAN 48220

March 28, 1974

Dr. Emerson W. Pugh
Executive Director
Committee on Motor Vehicle Emissions
National Academy of Sciences
2101 Constitution Avenue, NW
Washington, D.C. 20418

Dear Dr. Pugh:

This is in response to your letter of March 8, and the questions in it about our work with the Lean Reactor System. Your questions dealt largely with the potential we foresee for further emissions improvements beyond the present status as described in my letter of February 15. Answers to such questions, of course, are mostly forecasts and engineering judgments.

You first asked, "Is there potential for further reductions in emissions with the lean reactor system?"

We think so. In general, we believe that the 0.41 HC and 3.4 CO values probably can be reached, with some engines and cars, through further development work. However, we currently don't see good prospects for obtaining $NO_x$ values below about 1.2 g/mile. To expand on these opinions, our work has been mostly with engines in the 360-400 CID range and car weights of about 4500 pounds. We believe that lower emissions should be possible with smaller engines and lighter cars. Indications that a size factor probably exists can be found in results that have been made public on the Honda system in two engine sizes and also in results reported by DuPont on rich reactor systems applied to large and small cars. Some of our own work also suggests an importance of car size. We are now in the process of obtaining information in this area by developing a lean system for a European car of about 2000 cc displacement. This should give us actual test data on a smaller car in a few months. Right now we are carrying out the engine dynamometer development work on this engine and are finding excellent reductions from the stock engine. Of course, additional work with the complete vehicle will be needed to relate results to emission standards, and this work will be done in the next few months.

We feel that reactor improvements offer another area for further gains. We recently have designed and fabricated a new exhaust reactor that is lighter in weight (and hence lower in thermal inertia) and has other helpful design features. However, again it will be two or three months before we get enough data to judge how successful this work may be.

Furthermore, regarding lower emissions, even our present cars can be set to produce somewhat lower emissions of HC and $NO_x$ simply by spark retard. We do not consider this to be a desirable route, though, because of losses both in fuel economy and car performance. We believe that the emission levels we now have, together with fuel economy that is improved 10-18% relative to the 1973 counterpart car, present a much more realistic answer. As an example of the way variables can be compromised, we have found that we can lower HC about 30% and $NO_x$ about 10% if we operate lean reactor cars either without vacuum spark advance or by retarding the basic timing about six degrees. However, such spark retard also reduces fuel economy by about 7-13%. Similarly, if we were to target on higher $NO_x$ values, at about 3.5 g/mile, we can operate lean reactor cars without EGR and with no vacuum advance. In this case, fuel economy is not impaired and may be improved by as much as 4-5%. Such a change appears able to reduce HC by about 40%, but with an increase in $NO_x$ of about 120%. So, there are various options available for lowering some emissions at the expense of others, or of lowering some emissions at the expense of fuel economy, but we believe that these options are not as favorable on all counts as the present balance that we now use.

Your second question is, "How much reduction in emissions do you now incur from the improved carburetion and manifold and how much from the lean reactor?"

We can give estimates, but not actual measurements, in answer to this question. It may appear strange that we do not have definite data on this point, but there are reasons for this. Many factors must be optimized in the total system such as carburetion, choking, ignition timing, and EGR, and these interact with each other. In addition, many of these also interact with reactor performance by affecting both the amount of combustible material entering the reactor, as well as reactor temperature and warm-up rate. The problem is further compounded since the emission test cycle consists mostly of transient modes and there are thermal flywheel effects. Also, the vehicle must have good cold start and warmup performance, not only on the test cycle but also under all ambient conditions likely to be encountered in car use. This involves other interacting factors, such as the use of waste heat from the reactor to preheat the induction air, which affects choking. Therefore, all of this calls for a great deal of balancing and trading off of one variable against another in optimizing the system, and we have been doing work of this sort with all of the components in action. In our early work a number of years ago we did considerable testing of individual variables, but most of this work was done by emission test procedures that are now outdated and with emission systems that did not employ EGR. Because of all this, we do not now have data that breaks down and quantifies the effects of the separate systems on our present cars by current test procedures. We can make a reasonable estimate from various test experiences that the reactors (with exhaust port liners) in our present system reduce HC emitted from the combustion chamber by about 50-65%. Similarly, we estimate that CO is reduced by about 10-20%. Therefore, we can back-calculate and estimate that if the system were optimized without reactors and port liners, HC emissions would be about 1.2-1.7 g/mile rather than the 0.6 obtained with the total system. Similarly, in respect to CO, we would expect values of about 6.0-7.0 without reactors rather than the present value of about 5.3. The reactors have essentially no effect on the $NO_x$.

We can use these same values for estimating the individual reductions due to induction system modifications. Percentage reductions, of course, would depend on the emissions of the car before modification. If we selected as baseline a car set to 1974 standards (which, if measured by the 1975 CVS-CH procedure, would be expected to give about 3.0 HC, 28.0 CO and 3.1 $NO_x$) the reductions due to induction system improvements then would be about 45-60% on HC and 75-80% on CO.

Your next question was, "How much improvement could be expected in the individual system?"

Regarding carburetion and manifolding, we foresee possible improvements if good starting and warmup can be attained with less choking or temporary enrichment. In hot start tests, lean reactor emissions can be below the 1976 limits at normal spark advance, and in the range of 0.3 HC and 3.0 CO with slightly less spark advance. We are hopeful that our longer-range research will disclose new approaches to improved warmup and reduce the detrimental emissions effects of the cold start. In addition, past work and refinements have consistently produced incremental gains and we would forecast that more small gains remain to be realized before we reach the point that all remaining emissions are due to wall quenching or other effects within the cylinder that cannot be eliminated by good mixture preparation. It is possible, also, that factors within the combustion chamber, such as surface-to-volume ratio or turbulence, might be improved to reduce wall quenching but we have no well-defined leads on this now. With mass emissions, exhaust volume is important so vehicle factors offer other opportunities, not only in respect to size and weight, but also regarding drive ratios and car characteristics. So, there are many possible avenues for research but quantitative improvement predictions are extremely difficult to make and justify.

Regarding reactors, improvements can be visualized through lower warmup mass, better heat conservation, and improved geometry or flow patterns. We have work in progress to determine if these factors can be utilized, as mentioned earlier. Since reactor efficiencies appear to be still fairly low, as described above, there is room for improvement but we have no rational basis for making predictions of the magnitude that might be accomplished. Beyond reactor design, smaller engines and cars could also benefit reactor performance and total system performance. Smaller engines, operating at higher speeds and higher load factors, should provide higher reactor temperatures quickly, and may also provide conditions for better combustion within the cylinder itself. These factors remain to be studied.

Your next question is, "What are the characteristics and status of the advanced intake manifold that is under development?"

This manifold is so arranged that the entire fuel-air mixture from the primary carburetor venturi discharges initially into a small sheet metal box that is completely surrounded by exhaust gas in the exhaust crossover area. On cold starting, the exhaust crossover heat valve is closed and directs exhaust flow through the crossover. This quickly heats the box and imparts a high degree of heating to the air-fuel mixture. Later, after the engine warms up, the exhaust crossover valve opens so that exhaust no longer goes through the crossover and less heating is applied. The hot box, of course, vaporizes and thoroughly mixes the fuel-air mixture. Since EGR is introduced into the fuel-air mixture ahead of the hot box, the recirculated exhaust gas also is well mixed with the air-fuel mixture. Downstream of the hot box, the preheated mixture discharges back into the normal intake manifold passage and distributes much as a gas to the individual cylinders. Under heavy load conditions, the secondary venturis of the carburetor come into operation and discharge their mixture directly into the intake manifold without going through the heated box. This avoids the high mixture temperatures that otherwise might cause loss in volumetric efficiency and increased octane requirement. Since this system uses heat and does not rely entirely on atomization within the carburetor to promote fuel vaporization, we believe that this manifold is likely to permit good, lean operation with nearly conventional carburetion and will not require all of the features of the high velocity, high atomization, three-venturi carburetor that we developed for use with the lean reactor system. The use of nearly conventional carburetion should shorten, substantially, the time lag between an experimental system and a practical, producible system.

Regarding the status of our work with the new manifold, it is now operating in an experimental car that is also equipped with our high velocity three-venturi carburetor. We have found that the manifold does make improvement in driveability, emissions, and fuel economy. Emissions and fuel economy benefits probably relate to less need for choking. We now have engine dynamometer test work in progress in which this manifold is being tested with a commercial type, 4-barrel carburetor. This work is bearing out our expectations that this combination can achieve good mixture preparation and uniformity. We are finding a maximum total spread in air-fuel ratio between individual cylinder extremes of only 0.3-0.5 air-fuel ratios, which indicates excellent potential for good lean mixture operation. In addition, we are finding that even when the two primary barrels of a 4-barrel carburetor are badly out of balance with each other, as frequently happens in field adjustments, the improved manifold still maintains excellent mixture uniformity among cylinders. We project about three months of dynamometer development work to refine and calibrate a lean induction system around a conventional carburetor. Then we will install this system in a car and compare this simplified lean reactor system with our earlier experimental cars that were built around the experimental three-venturi carburetor. We see good prospects for extending this improved manifold concept to 4- and 6-cylinder engines as well, to take advantage of the lower emissions that we expect to attain from smaller, lighter weight cars.

Your final question is, "Will the system maintain the good cylinder-to-cylinder distribution under the accelerating and decelerating modes of operation?"

Experience with our 3-venturi carburetor, either with or without the new manifold, has indicated that good mixture preparation permits good distribution to be maintained under accelerating and decelerating conditions as well as at steady state. The best evidence of this is good, lean-mixture acceleration performance and the low emissions that such cars give during these transient modes. We expect the new manifold to behave similarly, but have yet to obtain detailed dynamometer test data.

Finally, I am attaching a revised copy of the Table 1 submitted with my letter of February 15. Additional fuel economy data have been obtained to fill some of the blank spaces in the original table.

We appreciate your interest in the lean reactor system and its distinct advantages. The advantages of this system, and the fact that its emissions at present do not yet quite meet the statutory standards for 1976-77, point out how important an accurate assessment of the needs, benefits and costs of any specific emission standards can be.

Very truly yours,

D. A. Hirschler
Director, Automotive Research

DAH:ew
Attach. 1

**Revised**

## TABLE 1

### Test Results with 360 Plymouth Fury III Cars
### 4500 lb. Test Weight

| | 1973 Model Non-Modified | 1971 Model Modified | | |
|---|---|---|---|---|
| | | Type 1(1) | Type 2(2) | |
| | | | Ethyl Data | Data from Car Mfg. |
| 1975 CVS Test: | | | | |
| HC, g/mile | - | 0.6 | 0.55 | 0.45 |
| CO, g/mile | - | 5.3 | 5.0 | 4.4 |
| $NO_x$, g/mile | - | 1.5 | 1.4 | 1.4 |
| 1972 CVS Test: | | | | |
| MPG, carbon balance | 9.2 | 10.8 | 11.2 | 11.0 |
| MPG, weighed fuel | 9.1 | 10.0 | 10.5 | 10.7 |
| Road Fuel Economy, mpg | | | | |
| City Route(3) | 10.3 | 12.0 | 12.2 | |
| City-Expressway Route(4) | 14.1 | 16.3 | 16.2 | |
| Fuel Economy Improvement, % | | | | |
| 1972 CVS Test, weighed | Base | 9.9 | 15.4 | |
| City Route | Base | 16.5 | 18.4 | |
| City-Expressway Route | Base | 15.6 | 14.9 | |

---

(1) Type 1 Modifications - Ethyl 3-V carburetor, modulated EGR, sheet-metal hotspot intake manifold, exhaust port liners, exhaust manifold reactors, starting sequence device, ignition advance controls.

(2) Type 2 Modifications - Same except: delete starting sequence device, delete sheet metal hotspot intake manifold, add hot-box insert in intake manifold (preheats mixture from carburetor primary venturi only).

(3) Average speed 23.4 mph, 2.2 stops per mile, 27.7 mile loop

(4) Average speed 36.7 mph, 0.36 stops per mile, 18.4 mile loop

DAH:ew
3-20-74

ETHYL CORPORATION
RESEARCH AND DEVELOPMENT DEPARTMENT
RESEARCH LABORATORIES • 1600 WEST EIGHT MILE ROAD
FERNDALE, MICHIGAN 48220

February 15, 1974

Dr. Emerson W. Pugh
Executive Director
Committee on Motor Vehicle Emissions
National Academy of Sciences
2101 Constitution Avenue N. W.
Washington, D.C. 20418

Dear Dr. Pugh:

We are pleased to respond to the request for information issued on January 24 by the Committee on Motor Vehicle Emissions.

As you probably know, our company has been active in research and development on the lean reactor system for emissions control for many years. On September 30, 1971, we met with the Emissions Control Panel of the Committee on Motor Vehicle Emissions. We discussed our lean reactor work with the Panel and furnished technical reports and publications. Later, on August 17, 1972, we provided a supplementary report to the Panel updating the earlier information. Since then, we have made more improvements in our experimental cars and have accumulated more data on fuel economy and durability which we are happy to report on.

As we have pointed out earlier, we believe that the lean reactor system has several important advantages: (1) It operates in the air-fuel ratio region between 17 and 18 : 1, which, of course, is a very favorable range relative both to fuel economy and emissions prior to after-treatment. (2) The system operates on fuels containing lead antiknocks. This makes it unnecessary to incur the losses in efficiency that accompany lowered compression ratios to accomodate nonleaded fuel. Furthermore, the losses in refining nonleaded fuels are avoided. (3) The system employs no catalysts and avoids all problems associated with catalysts such as cost, durability, deterioration, noble metal availability or emissions, and catalytic oxidation of $SO_2$. The only real disadvantage of the system is that a minor relaxation of the 1976-77 Emission Standards would be required to permit use of the lean reactor in its present state of development. (All indications are that the same problem also exists with presently available catalytic systems). Currently, in a 4500 lb. car and by the 1975 Test Procedure, typical emissions of our experimental cars are 0.6 HC, 5.0 CO and 1.4 $NO_x$. Fuel economy on either the 1972 CVS test cycle or on city or expressway road driving routes is 15 to 16% better than the corresponding 1973 production car. We feel that this is particularly important since many of the currently publicized comparisons on fuel economy are based on cars that meet the 49-state interim standards for 1975 rather than the more severe 1975 California interim standards that lean reactor cars meet.

Briefly, our modifications include a special high velocity carburetor and intake manifold changes (that provide the good mixture preparation that permits good driveability with lean mixtures), a modulated EGR system, exhaust reactors (that require no air pump because of the leftover oxygen from the lean mixtures), heat-conserving metal liners in the cylinder head exhaust ports, and control of spark advance to provide the best balance between emissions,driveability and economy. We are now in early stages of work with an even more advanced intake manifold concept and expect that this will make it possible for us to use only slightly modified conventional carburetion. We have not yet demonstrated this to be true, but have found the manifold modification to give benefits with our high velocity three-venturi carburetor.

I am enclosing a copy of our publication entitled "Lean Mixtures, Low Emissions and Energy Conservation" that we presented to the National Petroleum Refiners Association last April. This paper describes our modifications more specifically and also reports the emissions performance, fuel consumption and durability experience that we have obtained with lean reactor cars. Since this paper was written, we have devoted much of our effort to improving the fuel economy of the 360 CID Plymouth Fury identified as Car B in the NPRA paper. Therefore, I am attaching a separate table (Table 1) that compares our recent test results with this type of car against the non-modified 1973 model counterpart. The table includes both our own data and data obtained recently by a car manufacturer who is testing the car. The major changes made in the lean reactor system since the NPRA paper was prepared consist of new intake manifold design,recalibration of the EGR-spark advance relationships and deletion of the automatic starting sequence device since its added complexity was not warranted after the other two improvements were made. Figure 1, attached, shows details of the new intake manifold configuration, which is not described in the NPRA paper.

I also am enclosing a copy of EPA report #73-28 DWP, June, 1973, entitled "Evaluation of the Ethyl Corporation Lean Thermal Reactor System". This report presents the results of tests made on one of our experimental cars by the EPA Ann Arbor Laboratory, and shows results similar to our own.

Other EPA-sponsored studies of the lean reactor car were reported in March, 1973. The report is entitled "Aldehyde and Reactive Organic Emissions from Advanced Automotive Control Systems Vehicles, Under Inter-agency Agreement No. EPA-IAG-0188(D)". I am enclosing a copy of this report. In this test program, conducted by the Bartlesville Energy Research Center of the Bureau of Mines, a lean reactor car was tested over a range of ambient temperatures from 25° to 95° F. on several different fuels. Its emissions were characterized in detail and compared against results obtained with several other advanced emissions controlled vehicles provided by other organizations. Emissions of the lean reactor car (0.44 HC, 4.28 CO and 2.70 $NO_x$ under standard 1975 CVS test conditions) compared favorably with results given by the low mileage, catalyst-equipped vehicles used in the test program. Fuel economies were not measured.

Your request for information includes the topics of feasibility of mass producing systems, costs and maintenance requirements. The lean reactor system was one of the systems included in the study prepared for EPA by Aerospace Corporation and these factors are discussed in Aerospace Report TOR-0172(2787)-2, "Final Report and Assessment of the Effects of Lead Additives in Gasoline on Emission Control Systems Which Might be Used to Meet the 1975-76 Motor Vehicle Emissions Standards". We can add little to the information reported by Aerospace and the information in these areas that we have previously presented to your Committee. Obviously, the improved carburetion used in the lean reactor system would be the most time consuming to translate from the present experimental form to mass production. We believe that our current work with the improved intake manifold will greatly simplify the job of carburetion and probably make the system operable with only minor modifications of existing commercial carburetion. This should greatly ease problems of lead time and tooling in the production of lean reactor vehicles.

In summary, we believe that the lean reactor system has inherent advantages in fuel economy by virtue of its lean mixtures and its ability to utilize the efficiencies of high compression ratio engines. We also believe that the system has inherent advantages in emissions stability since only hardware components are involved and catalyst deterioration (which might not be perceived and corrected by the owner) is not a factor. In the climate of energy shortage we believe that the lean reactor raises serious questions as to the balance between the value of emissions standards slightly lower than the lean reactor now can meet and the penalties that will be involved in attempting to meet lower standards by systems other than the lean reactor.

We would be happy to discuss our work with the Committee or to provide further details should you desire.

Very truly yours,

D A Hirschler

D. A. Hirschler
Director, Automotive Research

DAH/ag
Encl. 5

## TABLE 1

### Test Results with 360 Plymouth Fury III Cars. 4500 lb. Test Weight

| | 1973 Model Non-Modified | 1971 Model Modified | | |
|---|---|---|---|---|
| | | Type 1(1) | Type 2(2) | |
| | | | Ethyl Data | Data from Car Mfg. |
| 1975 CVS Test: | | | | |
| HC, g/mile | - | 0.6 | 0.55 | 0.45 |
| CO, g/mile | - | 5.3 | 5.0 | 4.4 |
| $NO_x$, g/mile | - | 1.5 | 1.4 | 1.4 |
| 1972 CVS Test: | | | | |
| MPG, carbon balance | 9.2 | 10.8 | 11.2 | 11.0 |
| MPG, weighed fuel | 9.1 | 10.0 | 10.5 | 10.7 |
| Road Fuel Economy, mpg | | | | |
| City Route(3) | 10.3 | 12.0 | To be determined | |
| City-Expressway Route(4) | 14.1 | 16.3 | | |
| Fuel Economy Improvement, % | | | | |
| 1972 CVS Test, weighed | Base | 9.9 | 15.4 | |
| City Route | Base | 16.5 | To be determined | |
| City-Expressway Route | Base | 15.6 | | |

(1) Type 1 Modifications - Ethyl 3-V carburetor, modulated EGR, sheet-metal hotspot intake manifold, exhaust port liners, exhaust manifold reactors, starting sequence device, ignition advance controls.

(2) Type 2 Modifications - Same except: delete starting sequence device, delete sheet metal hotspot intake manifold, add hot-box insert in intake manifold (preheats mixture from carburetor primary venturi only).

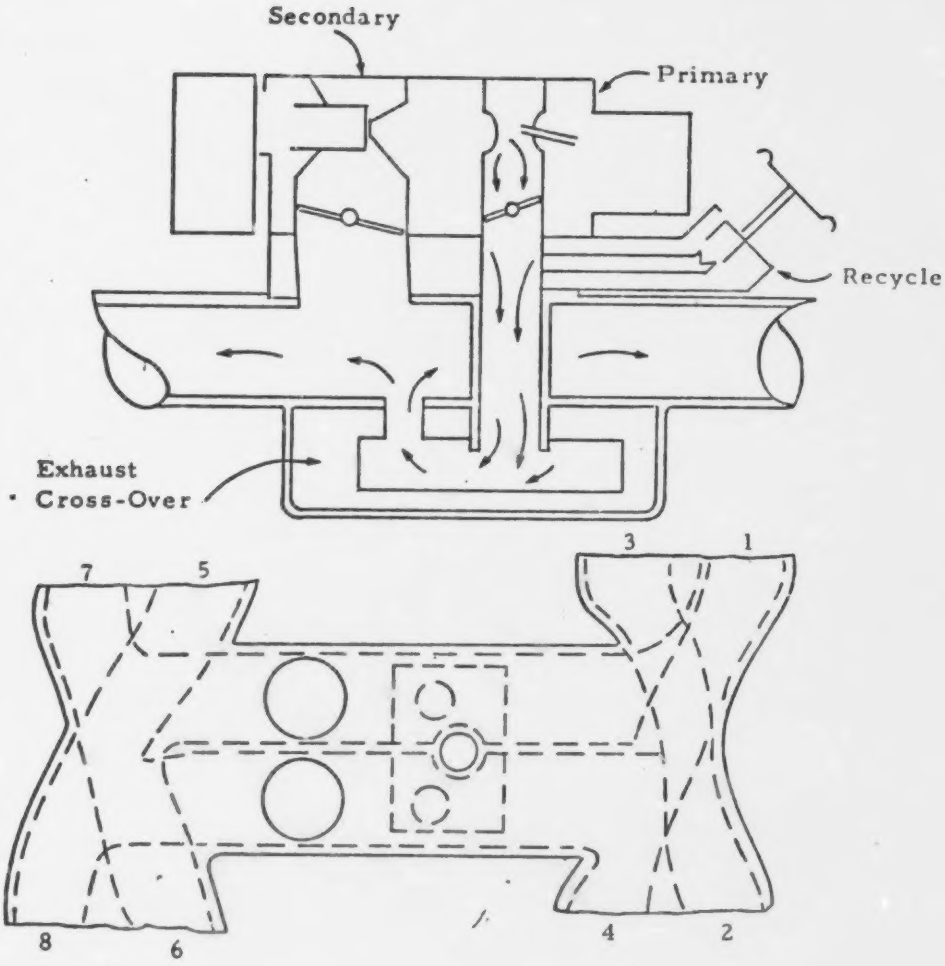
(3) Average speed 23.4 mph, 2.2 stops per mile, 27.7 mile loop

(4) Average speed 36.7 mph, 0.36 stops per mile, 18.4 mile loop

DAH/ag

Figure 1

# RECTANGULAR HOT BOX MANIFOLD FOR A 360 CID PLYMOUTH


Secondary
Primary
Recycle
Exhaust
Cross-Over
7
5
3
1
8
6
4
2

Cylinder-to-Cylinder Distribution Spread*

| Speed | Cruise A/F | Cruise F/A | Δ Distribution ΔA/F | Δ Distribution ΔF/A |
|---|---|---|---|---|
| Idle | 16.3 | .061 | 0.50 | .0020 |
| 15 | 17.5 | .057 | 0.49 | .0016 |
| 30 | 17.3 | .058 | 0.28 | .0009 |
| 50 | 16.6 | .060 | 0.47 | .0016 |

*A/F = air/fuel ratio
*F/A = fuel/air ratio

73-28 DWP

# Evaluation of the Ethyl Corporation Lean Thermal Reactor System

June 1973

Emission Control Technology Division
Office of Air & Water Programs
Environmental Protection Agency

## Background

The Ethyl Corporation has had a long term development program on emission control systems utilizing lean thermal reactors. Because their system represents a thoroughly tested example of this type of control technique the Office of Air and Water Programs contacted the Ethyl Corporation and requested an evaluation of their system. A test program was undertaken by the Test and Evaluation Branch.

## Device Description

This system incorporated lean carburetion, EGR, and thermal reactors. A more detailed description, prepared by Ethyl, is attached.

## Test Program

A 1972 Fury III with a 360 CID engine and the Ethyl lean thermal reactor system was tested. Three tests were conducted in accordance with the 1975 Federal Test Procedure (FTP) as described in the November 15, 1972, Federal Register. All test work was conducted at 4500 pounds inertia weight.

## Results

The results from the tests are reported in the attached table. These results demonstrate that emission levels well below 1975 interim standards can be achieved with this sytem. For comparative purposes an average 1972 FTP result was calculated using results from the first two bags of the reported 1975 test work. Comparison of this data with 1973 certification emissions levels and fuel economy are shown. This vehicle demonstrated significantly better emissions and fuel economy than a similar 1973 certification vehicle. General impression of vehicle driveability was good.

## Conclusions

Ethyl Corporation's lean thermal reactor system installed on a 1972 Fury (360 CID engine) demonstrated the potential for achieving emission levels well below 1975 interim standards. This vehicle as equipped with Ethyl's system also demonstrated good fuel economy and driveability and was lead insensitive. The vehicle tested did not, however, meet either the statutory 1975 or 1976 standards.

## Emissions and Fuel Economy
### 1975 FTP

| | HC gm/mi | CO gm/mi | NOx gm/mi | $CO_2$ gm/mi | Fuel Consumption mpg |
|---|---|---|---|---|---|
| Test 1 | .78 | 5.93 | 1.42 | 756.49 | 11.23 |
| Test 2 | .78 | 5.51 | 1.30 | 769.51 | 11.05 |
| Test 3 | .87 | 5.77 | 1.42 | 746.80 | 11.96 |
| Average | .81 | 5.74 | 1.38 | 757.60 | 11.41 |
| 1975 Interim Standards | 1.5 | 15.0 | 3.1 | --- | --- |
| 1976 Interim Standards | 0.4 | 3.4 | 0.40 | --- | --- |

## Emissions and Fuel Economy
### 1972 FTP

| | HC gm/mi | CO gm/mi | NOx gm/mi | $CO_2$ gm/mi | Fuel Consumption mpg |
|---|---|---|---|---|---|
| Avg. 3 tests | 1.06 | 7.07 | 1.42 | 755.91 | 11.23 |
| 1973 Cert Results | 2.6 | 38.0 | 2.4 | --- | 9.7 |

(ETHYL CORPORATION REPORT)

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# APPENDIX

## LEAN REACTOR SYSTEMS

### Carburetion, Mixture and Air Heating, EGR, Ignition Advance, and Automatic Starting Sequence Device

### Carburetion

The effectiveness of the lean reactor system depends primarily on improved carburetion. The advantages of lean operation have long been known; but, with conventional carburetion, problems can limit its usefulness. Problems in making conventional engines lean are that some cylinders may become much leaner than others, or mixtures within the individual cylinders may vary. By causing combustion to be poor in some cylinders, this can produce an increase in hydrocarbon emissions rather than the expected decrease. Driveability difficulties also can result from poor combustion in the excessively lean cylinders. Both of these problems tend to increase when exhaust gas is recirculated for reduction of $NO_x$. Another problem is that, when an engine is made only moderately lean, $NO_x$ increases. However, this increase occurs only until air-fuel ratios of 15-16:1 have been reached and, as the mixture is made leaner beyond this point, $NO_x$ decreases. Earlier research showed that problems of lean mixtures could be overcome and the limits of satisfactory lean operation extended if the air-fuel mixture was very well mixed and evenly divided among the cylinders. The 3-venturi carburetor was developed to provide a high degree of atomization and mixing, along with close-tolerance metering of the air-fuel mixture. This carburetor utilizes high air velocities for mixing. Other design characteristics also help. These include the geometry of the fuel nozzle and the use of perforations in the primary throttle plate through which the mixture passes under some conditions. Also, a mixing tube extends into the intake manifold beneath the primary throttle.

High air velocities are produced by the use of a small primary venturi for light loads and two variable secondary venturis for higher power conditions. Thus, the high velocities present under all conditions not only provide mixing but also give strong metering signals at any engine condition. These signals, in turn, promote metering accuracy. In addition, the strong venturi signal permits elimination of the separate idle system and allows fuel for idling and light load conditions to be provided through the main nozzle of the primary venturi, which also benefits mixing. Other refinements incorporated in the carburetor include a device for temperature-compensating the idle mixture ratio, an internal control to increase mixture flow during deceleration, and a temperature-modulated choke that closely relates both the degree and duration of choking to engine and under-hood temperatures. Use of these systems, even in conjunction with EGR, permits an idling air-fuel ratio of about 17.2:1 and operating air-fuel ratios of 17-18:1 across the speed range. Enrichment to 12:1 A/F occurs at full power.

## Mixture and Air Heating

Quick warm-up is a critical factor in advanced emission control systems. Several systems are used in the lean reactor to improve performance and emissions during the first few minutes after starting. As mentioned earlier, choking is carefully regulated and the idle air-fuel mixture is temperature compensated. In addition, the intake manifold is modified in the hot-spot section beneath the carburetor throats to transfer heat rapidly from the exhaust gas side of the manifold crossover to the intake side. This provides more rapid vaporization of fuel on the cold start. This modification consists of discs of finned stainless steel that replace portions of the normal cast iron structure in the hot-spot area. A crossover heat control valve directs exhaust gas from one side of the engine through the crossover and out the other side during the cold-start period. After warm-up, this valve opens and the exhaust gas bypasses the hot-spot area. Carburetor air also is preheated rapidly by the use of a muff-type preheater installed at one reactor outlet. The conventional temperature control valve in the air cleaner opens after warm-up to maintain carburetor air at the normal temperature.

## Exhaust Gas Recirculation System

A modulating EGR system is used to vary the amount of EGR used during different driving modes. The primary signal used to modulate EGR is venturi vacuum--a measure of engine airflow. This vacuum signal operates a vacuum motor and, in turn, a contoured cam that positions a pintle valve located between the exhaust source and the intake manifold. This basic system is subject to additional controls that actuate a solenoid valve that either blocks or opens the vacuum line to the vacuum motor. These controls are shown in Figure A-1. A temperature-sensing switch in the air cleaner blocks out EGR until carburetor air temperature exceeds 60°F, at which time the engine can tolerate the dilution. This overcomes cold-start problems and drive-away deficiencies at low temperatures. Similarly, to prevent problems caused by charge dilution from exhaust gas immediately after the engine starts, a time delay in the circuit prevents the onset of EGR until 40 seconds after the engine starts. EGR also is shut off during idle and heavy deceleration by a throttle switch that senses the closed throttle position. Under full-throttle conditions, EGR is shut off by a manifold vacuum switch as a safety measure to permit full power development. A speed switch also interrupts EGR use at speeds above 60-65 mph. Interruption of EGR at high speeds causes reactor temperatures to decrease by about 200°F. Thus, this control permits the use of high reactor temperatures at moderate speeds without excessive temperatures at extremely high speeds, and contributes both to good performance of the system and durability of the reactors.

## Ignition Advance System

Figure A-2 shows the system used to control distributor vacuum advance. A solenoid valve opens or closes the vacuum line to the vacuum advance unit and permits vacuum advance under some operating conditions but not under others. EGR and ignition timing are related to each other to maintain good driveability and emission control. Under stabilized engine operating temperatures, no vacuum advance is applied until EGR has begun to flow. Then the solenoid opens and vacuum advance is applied. Spark advance coming on at this point offsets the sluggishness of EGR. However, when the engine is cold and EGR has not yet become operative, vacuum advance is desirable for good engine starting and performance. Thus, temperature overrides are used to apply vacuum advance regardless of EGR until the temperatures of both the engine block and the air cleaner exceed 60°F. Similarly, to prevent overheat problems, vacuum advance is applied if engine coolant temperature exceeds 220°F. Another circuit maintains vacuum advance at high speeds regardless of EGR. Characteristics of the vacuum advance have been modified to provide greater-than-normal advance when manifold vacuum is low. This is done to compensate for the low manifold vacuums that accompany lean mixtures and EGR. The distributor also incorporates a solenoid that can retard ignition timing 10°. This solenoid is actuated for a few seconds after starting and is controlled by the automatic starting sequence device (ASD), as described below.

## Automatic Starting Sequence Device

To obtain low emissions, it is essential that an engine warm up quickly with minimum choking. In some experimental cars, momentary use (about 10 seconds) is made of higher speeds, retarded timing and greater throttle opening during initial starting to hasten warm-up. Retarded timing has three effects. One is to reduce hydrocarbon emissions. A second is to increase the temperature of the exhaust gas. The third is to reduce engine power output, which permits a larger throttle opening for a given engine speed. Figure A-3 shows how these factors have been combined into a simple, automatic starting sequence device. Physically this device consists of a small vacuum-operated piston mounted near the carburetor. Vacuum is applied through a solenoid valve. When the engine first starts, the solenoid opens and vacuum is applied to the piston. The piston advances the throttle in a manner similar to the conventional choke-operated high-speed idle. At the same time, the piston closes electrical contacts to actuate the solenoid that retards the distributor about 10° and blocks off vacuum advance. Thus the device causes a high idle speed with a heavily retarded spark for about 10 seconds after starting. Then the system disengages and will not reindex to repeat the cycle unless the ignition switch has been turned off for a few seconds. Thus it does not complicate operation in the event of an engine stall.

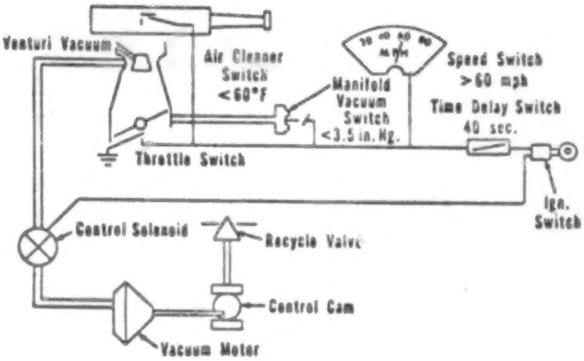
Venturi Vacuum
Air Cleaner Switch <60°F
Manifold Vacuum Switch <3.5 in. Hg.
MPH
Speed Switch >60 mph
Time Delay Switch 40 sec.
Throttle Switch
Ign. Switch
Control Solenoid
Recycle Valve
Control Cam
Vacuum Motor

Figure A-1. Exhaust Gas Recycle System

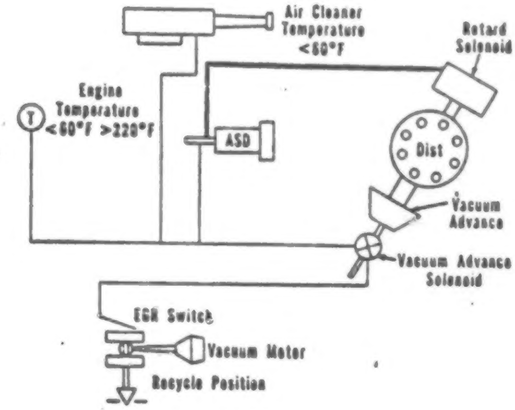
Air Cleaner Temperature <60°F
Retard Solenoid
Engine Temperature <60°F >220°F
T
ASD
Dist
Vacuum Advance
Vacuum Advance Solenoid
EGR Switch
Vacuum Motor
Recycle Position

Figure A-2. Modified Ignition System

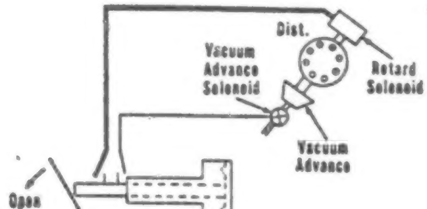
Dist.
Vacuum Advance Solenoid
Retard Solenoid
Vacuum Advance
Open
Throttle Lever
Solenoid
Vac Tank
Time Delay 8 sec.& Temp. Switch
Ignition Switch

Figure A-3. Automatic Start Device (ASD)

# Confirmatory Test of "Dresserator" Emission Control System

Project 235

May 1973

California Air Resources Board
Vehicle Emissions Laboratory
9528 Telstar Avenue
El Monte, California 91731

# Confirmatory Test of "Dresserator" Emission Control System

## Project 235

## Introduction

A carburetor with a variable area venturi and pressure fuel-feed system has been developed by the Dresser Industries, Inc., Environmental Technology Division. This air-fuel metering device is referred to as the "Dresserator". When used in conjunction with some degree of engine modification, the device is claimed to meet the 1975 California emission standards without the use of catalytic muffers.

A 1971 Ford (Table I) equipped with a prototype "Dresserator" system was delivered to the Air Resources Laboratory on May 24, 1973, by Messrs. L. P. Berriman, James Pence, and Ron Armstrong of the Dresser Industries. A cold start 1972 Federal CVS test was conducted on May 25, 1973.

## System Description

The "Dresserator" emission control system included a special carburetor with a mechanically actuated variable area venturi. The venturi size was varied to maintain the flow of air and fuel mixture at the speed of sound through the throat. The sonic throat was claimed to aid in fuel mixing and distribution. The fuel was injected from a spray bar upstream of the venturi. Fuel flow rate and venturi size was controlled by the foot accelerator pedal.

Other engine modifications were: air cleaner and intake manifold modified (to match the Dresserator carburetor configuration), vacuum spark advance removed, and exhaust manifolds enlarged. The larger exhaust manifolds allowed longer gas residence time for additional oxygenation of the residual air-fuel mixture.

Table I

Vehicle Data

| | |
|---|---|
| Manufacturer | Ford Motor Co. |
| Model | 4 Door - Galaxie |
| Year | 1971 |
| License | California 028 DLL |
| Odometer | 20458 |

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### Table I (cont'd)

| | |
|---|---|
| Carburetor | Special "Dresserator" |
| Transmission | Automatic |
| Accessories | Air Conditioning<br>Power Steering<br>Power Brakes |
| Emission Control System | PCV - Positive Crankcase Ventilation<br>DDVA - Dual Diaphragm Vacuum Advance*<br>Carbon Storage Evaporative Emission Contro |

*Note: Vacuum advance disconnected.

## Test Program

One cold start 1972 Federal Constant Volume Sample (CVS) test was conducted. A baseline test was not possible due to the extensive modifications made to the engine. The fuel used was Indolene Clear (91 Octane). Gas samples of diluted exhaust were collected and analyzed for hydrocarbons by FIAD, carbon monoxide by NDIR, and oxides of nitrogen by chemiluminescent analyzer.

Vehicle pre-test engine data were:

Idle speed - 620 RPM
Idle CO - 0.2%
Dwell - 30°
Ignition Timing - 7° BTDC (distributor vacuum disconnected)

## Results

The calculated CVS test results were:

| Exhaust Pollutant | ARL Test | Typical Dresser Data* | 1975 Std. |
|---|---|---|---|
| HC, grams/mile | 0.32 | 0.35 - 0.40 | 0.9 |
| CO, grams/mile | 4.68 | 6.9 - 7.5 | 9.0 |
| NOx, grams/mile | 1.58 | 1.2 - 1.6 | 2.0 |

*Ref. Letter, Englert to Chipman, dated May 24, 1973.

Fuel consumption during the test was 4.29 pounds (1951 grams). This corresponds to approximately 10.8 mile/gal.

## Conclusion

The emission levels obtained from a 1971 Ford, 351 CID engine with a prototype "Dresserator" device, in addition to the factory installed emission control systems, confirmed the level of emissions obtained by Dresser Industries, Inc.

No adverse effect on vehicle driveability was detected during the dynamometer test.

Research Laboratories
General Motors Corporation
General Motors Technical Center
Warren, Michigan 48090

October 15, 1973

Mr. Max M. Roensch
31020 Huntley Sq. E., Apt. 213
Birmingham, Michigan 48009

Dear Max:

You requested additional details regarding the IVT engine fuel consumption data which were published in 1968. Enclosed are copies of the original quantitative plots which I believe will best serve your requirements. Included are IVT BSFC vs. BMEP "fishhook" data for 800, 1200, 1600, 2000, and 2800 RPM, at MBT spark settings. (The 1200 RPM data were included as Figure 16 in our SAE paper.) Each data point has the respective engine air-fuel ratio (A/F) indicated. The overlapping character of these fishhooks shows the retention of efficiency at very lean mixtures for the Sonic Throttling Process.

For comparison, BSFC fishhook data for conventionally throttled operation are included for the speeds of 1200 and 1600 RPM. These data were obtained on the same engine at essentially the same time by shifting to full valve lift and closing the conventional manifold throttle. The 1200 RPM data corresponds to Figure 17 of our paper. The typical lean mixture fuel consumption increase from the best BSFC envelope is apparent from these fishhooks at both speeds. Conventional operation of this modified 400 CID, 10:1 CR 1968 Pontiac engine was not evaluated at the other speeds, unfortunately.

Since it is the comparison between conventional and Sonic Throttling as they affect BSFC that is of interest to you, I have included our original crossplots of the data of Figures 16 and 17 of the paper. On two graphs, the conventional and Sonic Throttling 1200 RPM BSFC data are compared at BMEP values of 15, 20, 30, and 40 psi. Data were plotted for each integer air-fuel ratio between 13:1 and 23:1.

These crossplots show how the fuel consumption advantage of Sonic Throttling increases markedly at the lighter loads. At 20:1 air-fuel ratio, for instance, the conventional throttling fuel consumption was over 23 percent greater at 15 psi BMEP. At road load (about 20 psi) fuel consumption was over 16 percent greater at 20:1 A/F, and about 5 percent greater everywhere at the richer A/F. Under mild acceleration (30 psi), conventional throttling fuel consumption was about 5 percent greater over most of the mixture ratio range. Under full load operation, both engine operating modes are identical.

I would like to caution you however, Max, that making these one-for-one comparisons at arbitrary A/F can be misleading. For instance, at the road load condition (20 psi BMEP), conventional throttling was shown to suffer 16 percent higher fuel consumption at 20:1 A/F. Since the conventional engine does not produce useful power at 20:1 A/F (due to cyclic combustion variations which produce surge and other driveability problems), this comparison is somewhat academic. Also, as noted in our paper, this fuel injected, modified engine did not produce the full valve lift at "wide open throttle", thereby favorably augmenting the lean engine operation during the so-called conventional mode of operation. Nonetheless, the conventional mode of operation, as you know, does not produce useful automotive power at mixture ratios much leaner than 17:1 A/F.

I trust that this information will suffice for your purposes. If you have any questions about these data, we will be glad to be of further assistance.

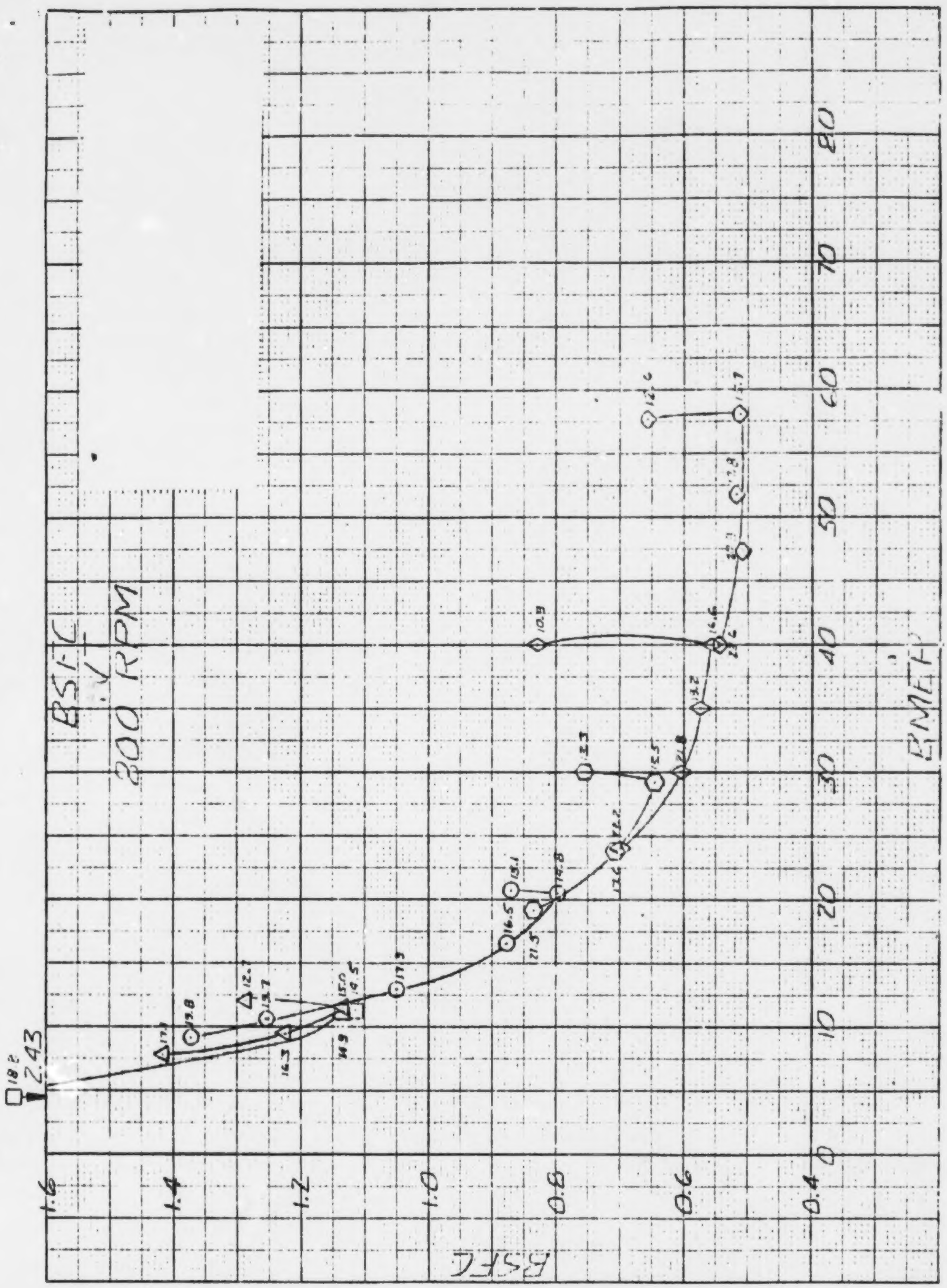
Yours very truly,

Donald L. Stivender
Engine Research Department

DLS:ds

Enclosures (9)

cc: J. B. Bidwell
W. G. Agnew
C. A. Amann
P. T. Vickers


BSFC v 300 RPM
BMEP
BSFC
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
10
20
30
40
50
60
70
80
2.43
182
13.8
12.7
13.7
16.3
15.0
14.5
14.9
17.3
16.5
21.5
13.1
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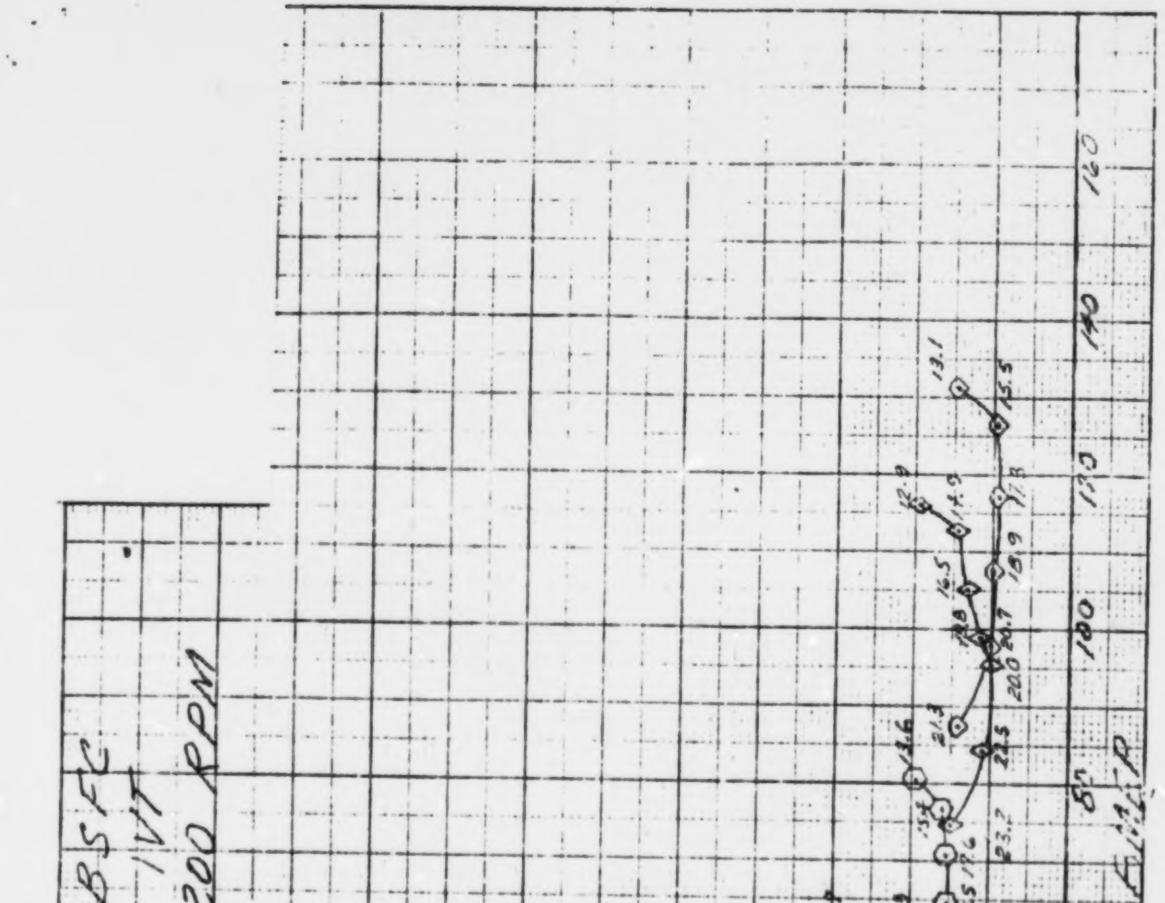
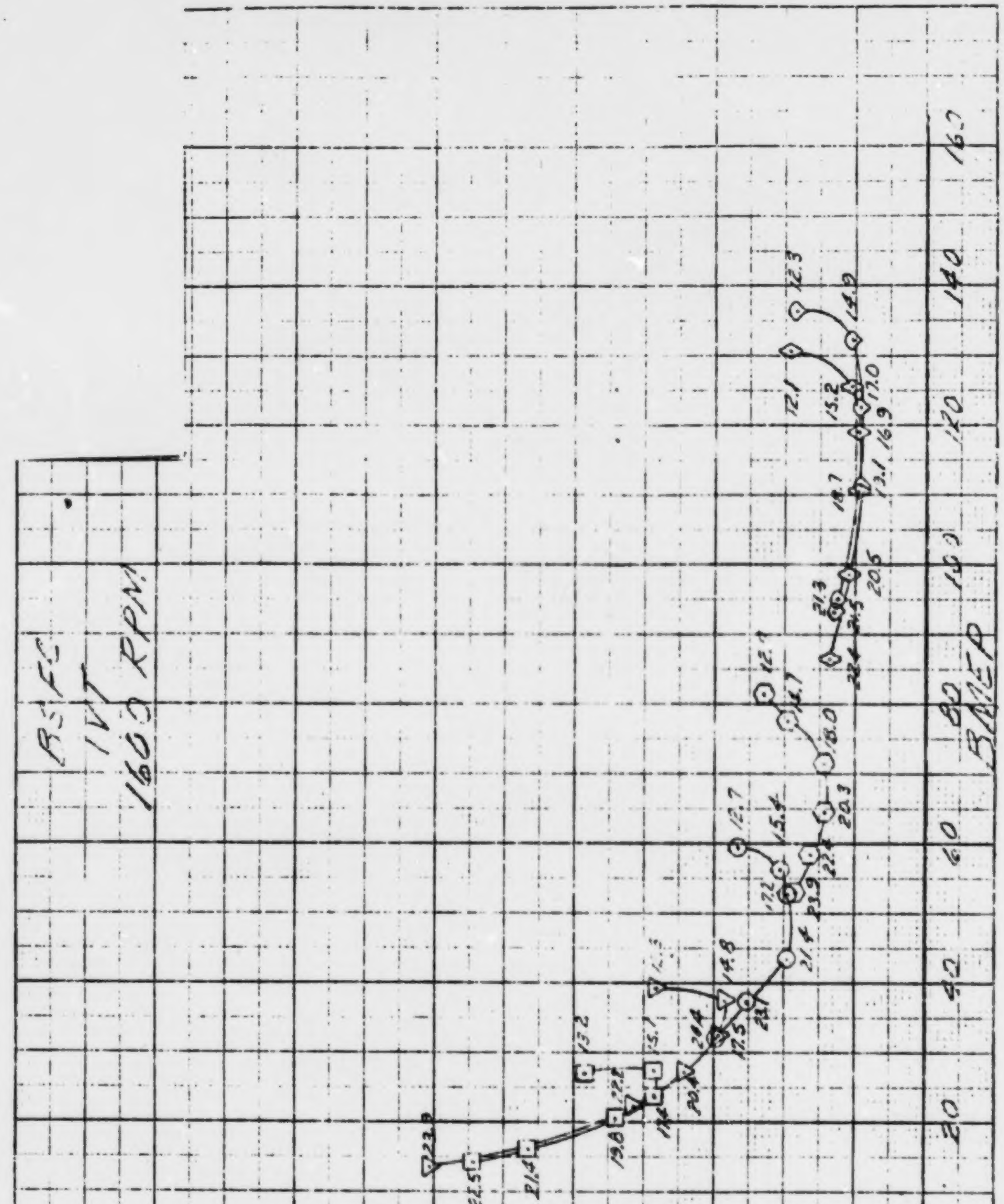
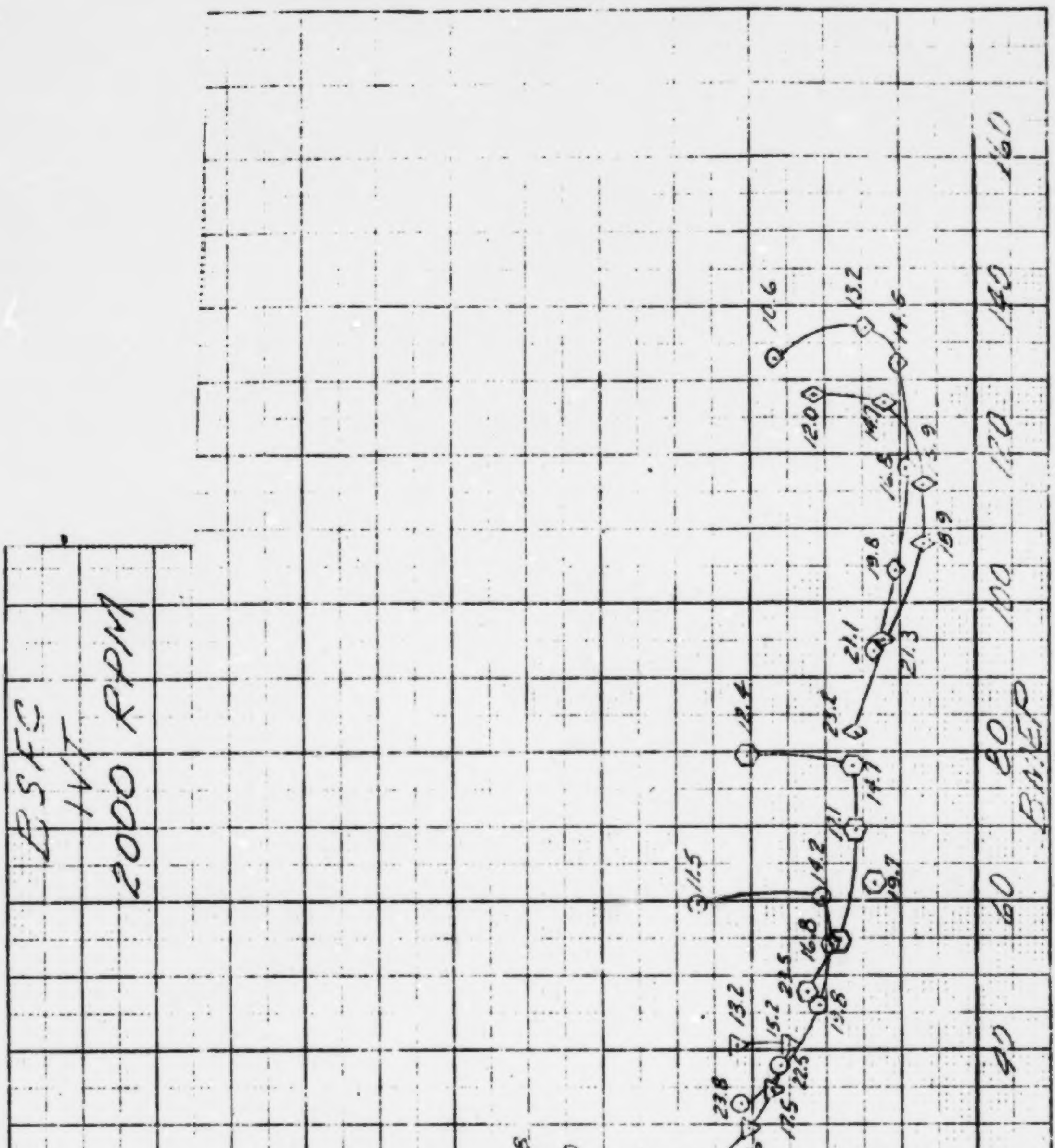
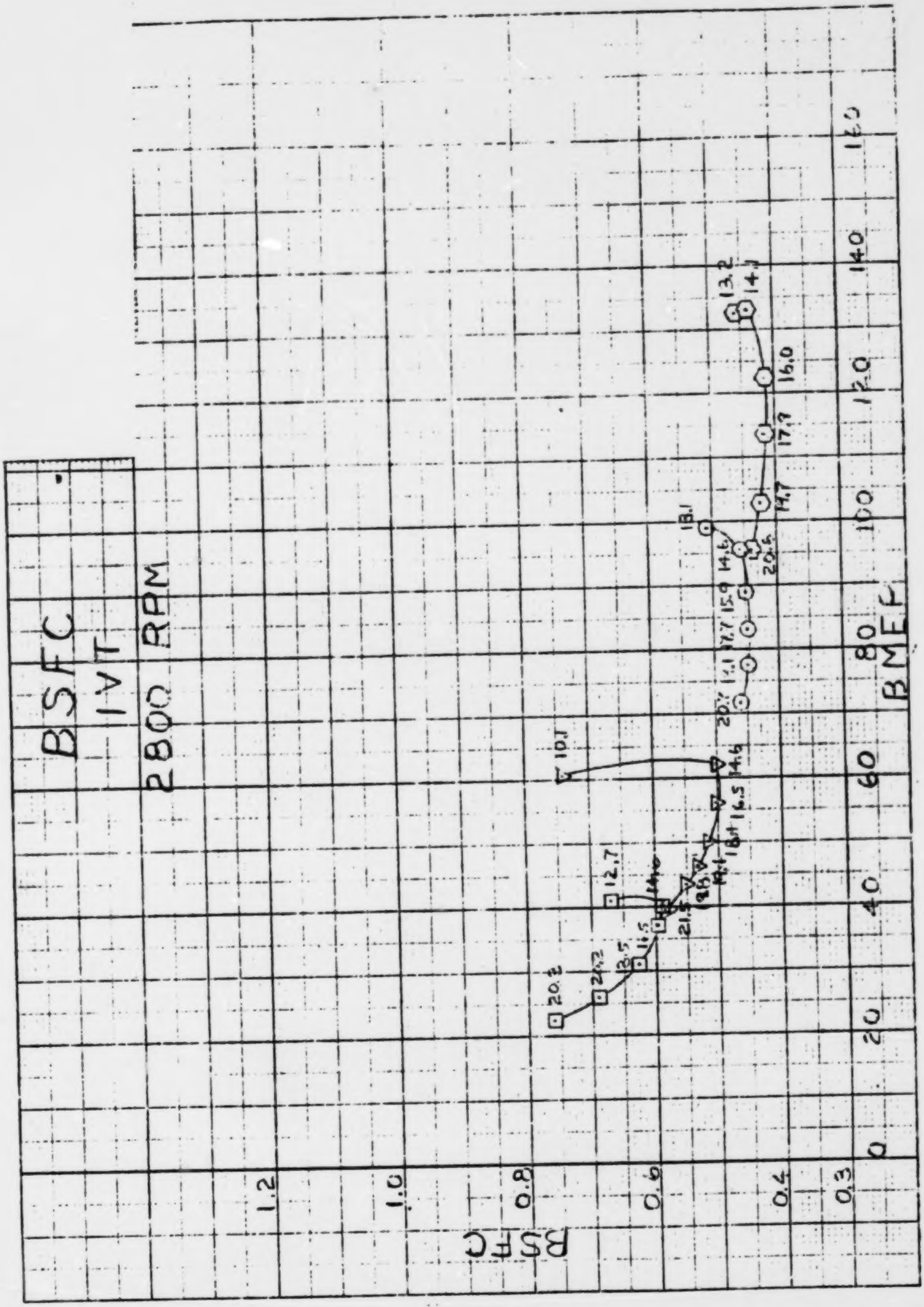
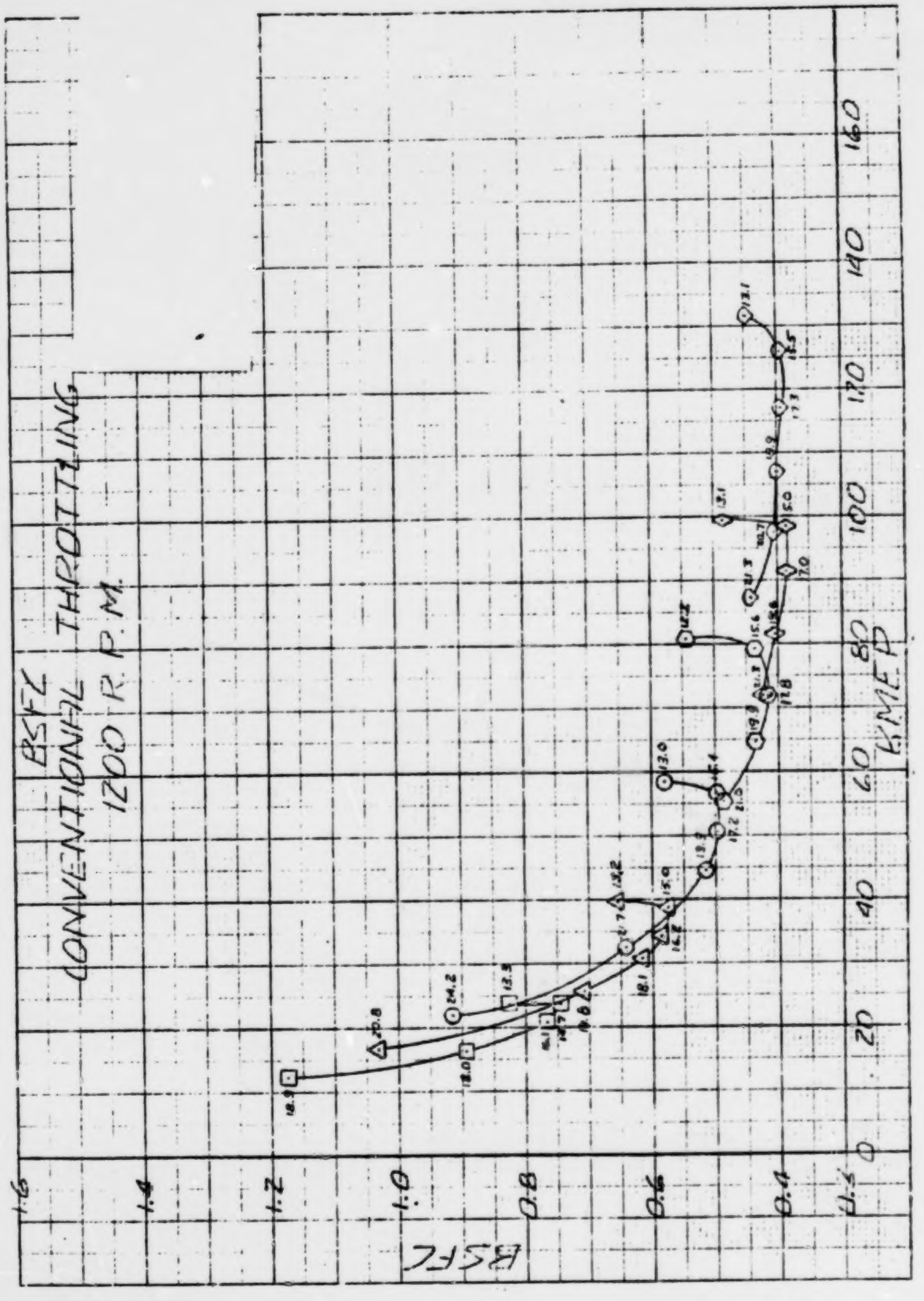
12.2
12.6
13.3
15.5
21.8
13.2
10.9
14.6
23.2


BSFC
IVT
1200 RPM
BSFC
1.6
1.4
1.2
1.0
.08
0.6
0.4
0.3
0
20
40
60
80
100
120
140
160
B.H.P

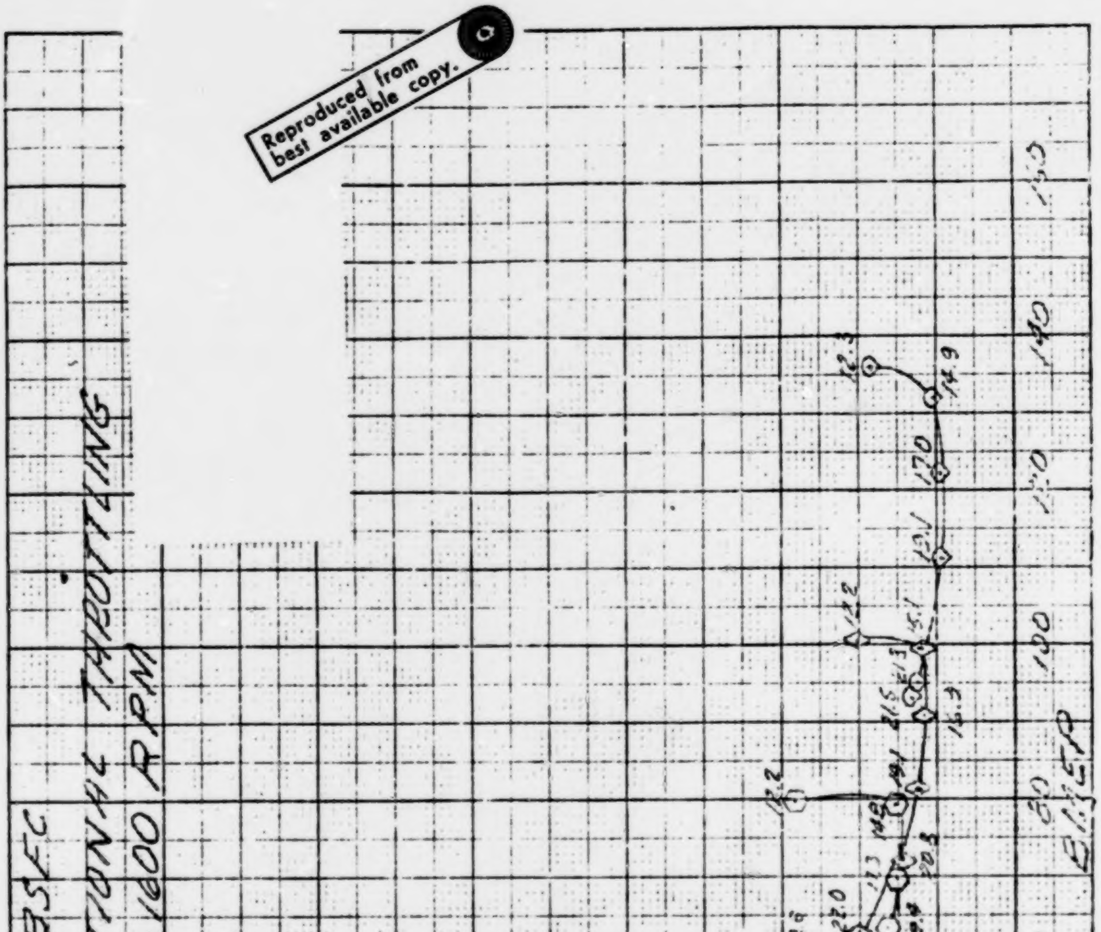

BSFC
IVT
1600 RPM
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.3
0
20
40
60
80
100
120
140
160
BMEP
BSFC
23.9
22.5
21.3
19.8
17.8
17.2
13.2
15.7
20.4
21.4
17.5
14.8
12.3
22.1
12.7
15.4
17.2
21.4
23.9
22.2
20.3
18.0
14.7
12.9
22.4
21.5
21.3
20.5
18.7
13.1
16.9
15.2
17.0
12.1
14.9
12.3


BSFC
IVT
2000 RPM
BSFC
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.3
BHP
0
20
40
60
80
100
120
140
160
20.2
17.1
16.1
12.8
14.0
21.6
19.6
23.8
17.5
13.2
15.2
22.5
23.5
19.8
16.8
11.5
14.2
17.1
19.7
12.4
14.7
23.2
21.1
21.3
19.8
19.9
16.8
3.9
12.0
14.1
10.6
13.2
14.6

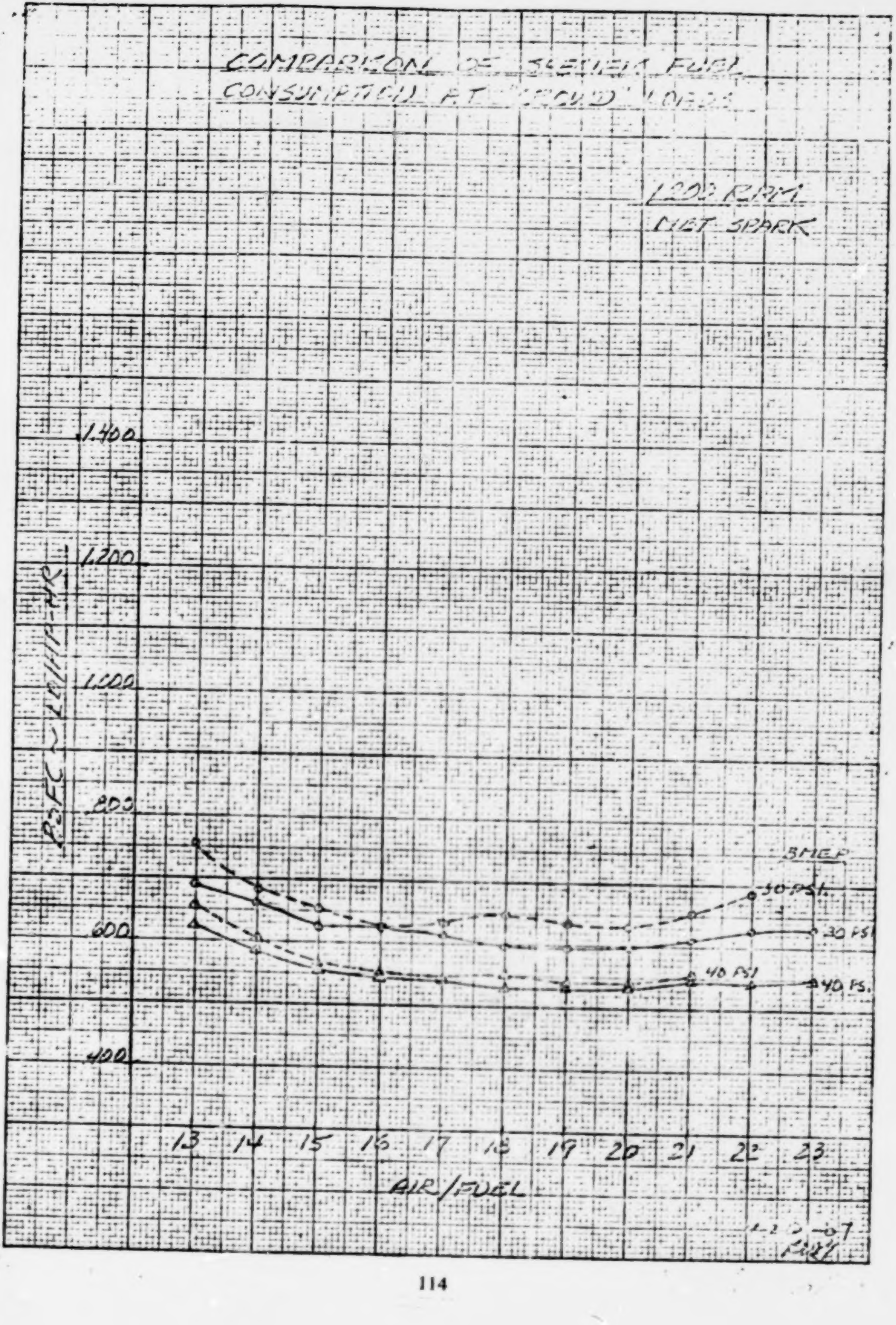

BSFC
IVT
2800 RPM
BSFC
1.2
1.0
0.8
0.6
0.4
0.3
BMEP
0
20
40
60
80
100
120
140
160
20.2
20.2
13.5
11.5
12.7
14.0
21.5
19.5
19.1
18.1
16.5
14.6
10.1
20.7
19.1
17.7
15.9
14.6
13.1
20.5
14.7
17.7
16.0
14.1
13.2

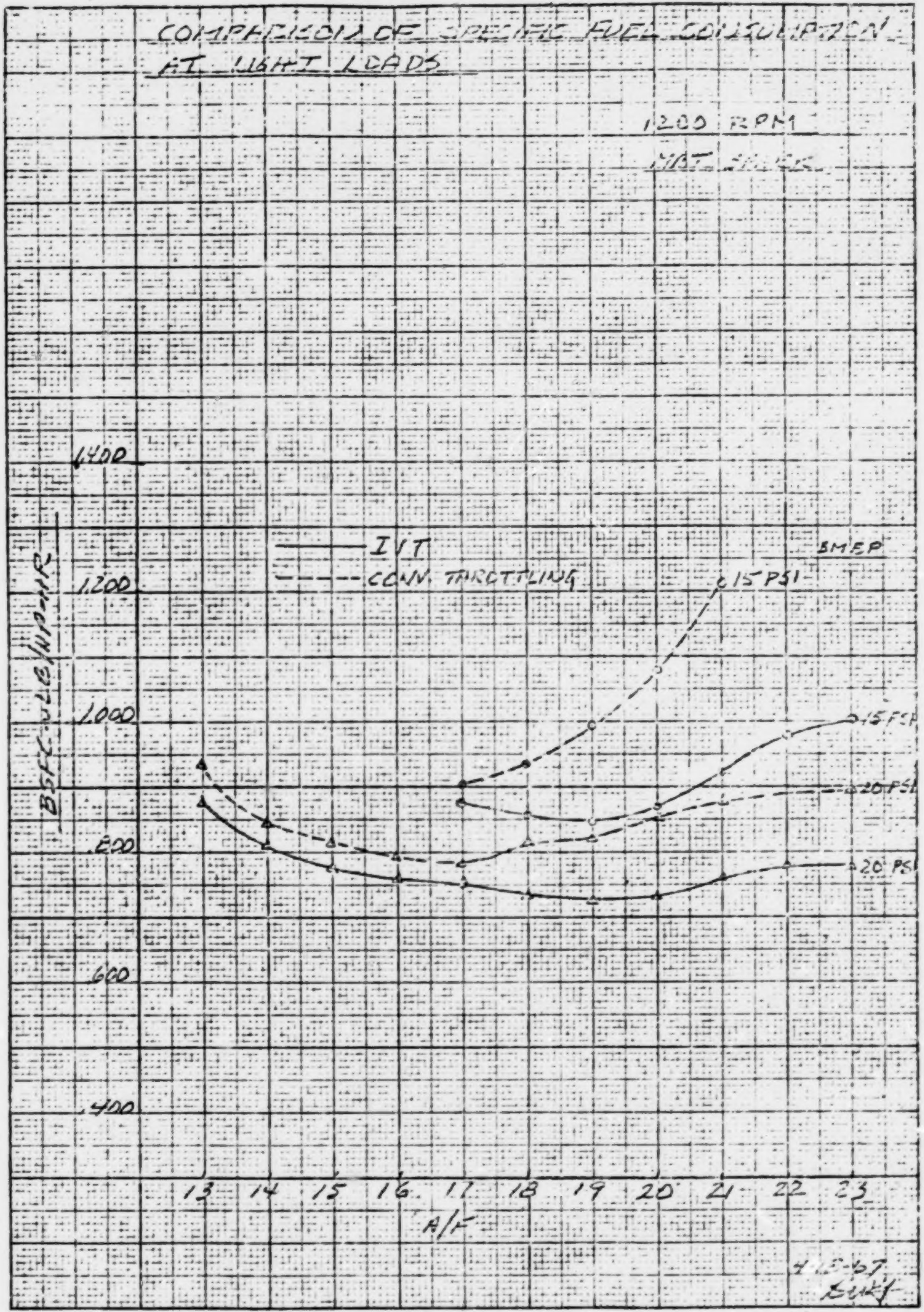

BSFC
CONVENTIONAL THROTTLING
1200 R.P.M.
BSFC
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
20
40
60
80
100
120
140
160
BMEP

Reproduced from best available copy.



No. 2 7 x 10 INCHES
KEUFFEL & ESSER CO.





COMPARISON OF SPECIFIC FUEL CONSUMPTION AT LIGHT LOADS

DEC 5 1973

jpl
**JET PROPULSION LABORATORY** *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

29 November 1973

Refer to: 38-73-36

Mr. Donald A. Hurter
Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts 02140

Dear Mr. Hurter:

In response to your request, I am sending you additional data on the JPL high-efficiency, low-pollution engine project. Engine dynamometer test results are given for level-road-load conditions using bottled hydrogen. This is the mechanization that is now in our bottled-hydrogen vehicle. Although successful engine dynamometer tests have been made with the engine/hydrogen generator combination, it would be premature to supply you this preliminary data.

The JPL test engine is a stock 1973 Chevrolet V-8 with 350 cubic inches displacement. With the exception of the PCV system, all stock emission devices were removed from the engine during development of the JPL induction system.

As you correctly point out, it is necessary to estimate the penalty for generation of the hydrogen when evaluating the potential economy gains using the JPL system. The product gas of the current hydrogen generator contains carbon monoxide, methane, and other hydrocarbons in addition to hydrogen. The heating values of the combustibles in the product gas are about 67 percent of the heating value of the gasoline supplied to the generator. Hydrogen contains approximately 35-40 percent of the heating value of the product gas. It is anticipated that significant gains in hydrogen generator performance will be made during the coming months.

The JPL bottled-hydrogen vehicle, a 1973 Chevrolet Impala sedan, has been tested through the EPA driving cycle. Using the results of

*Telephone 354-4321* *Telex 675421* *Twx 910-588-3294*

this EPA test and the current hydrogen generator performance, a 15-20 percent improvement in the baseline vehicle economy is projected. It does however, run at a higher hydrogen/gasoline ratio than is really required. This, of course, reduces economy in such a projection.

I hope the enclosed information will be of some value in your fuel economy study for the Department of Transportation and the Environmental Protection Agency, We would appreciate getting information related to your study as soon as it is available.

Sincerely,

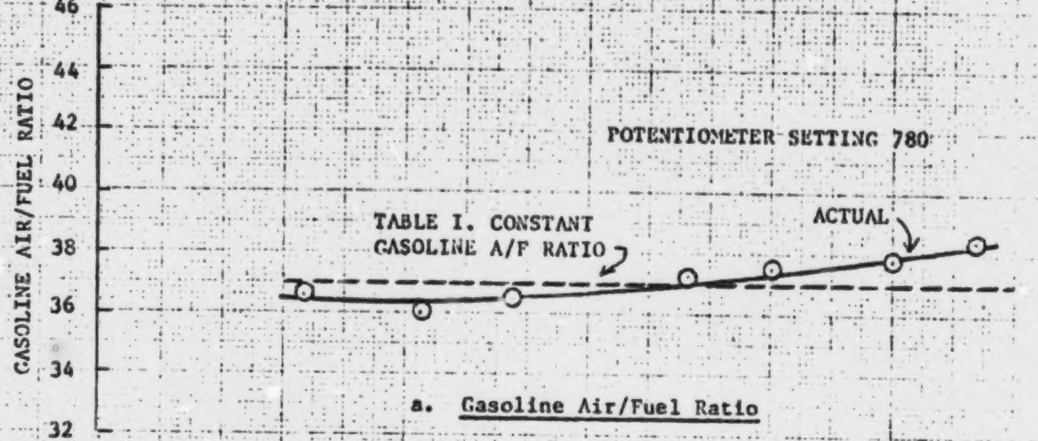
H E Cotrill

Harry E. Cotrill
Manager
Low-Pollution Engine Project

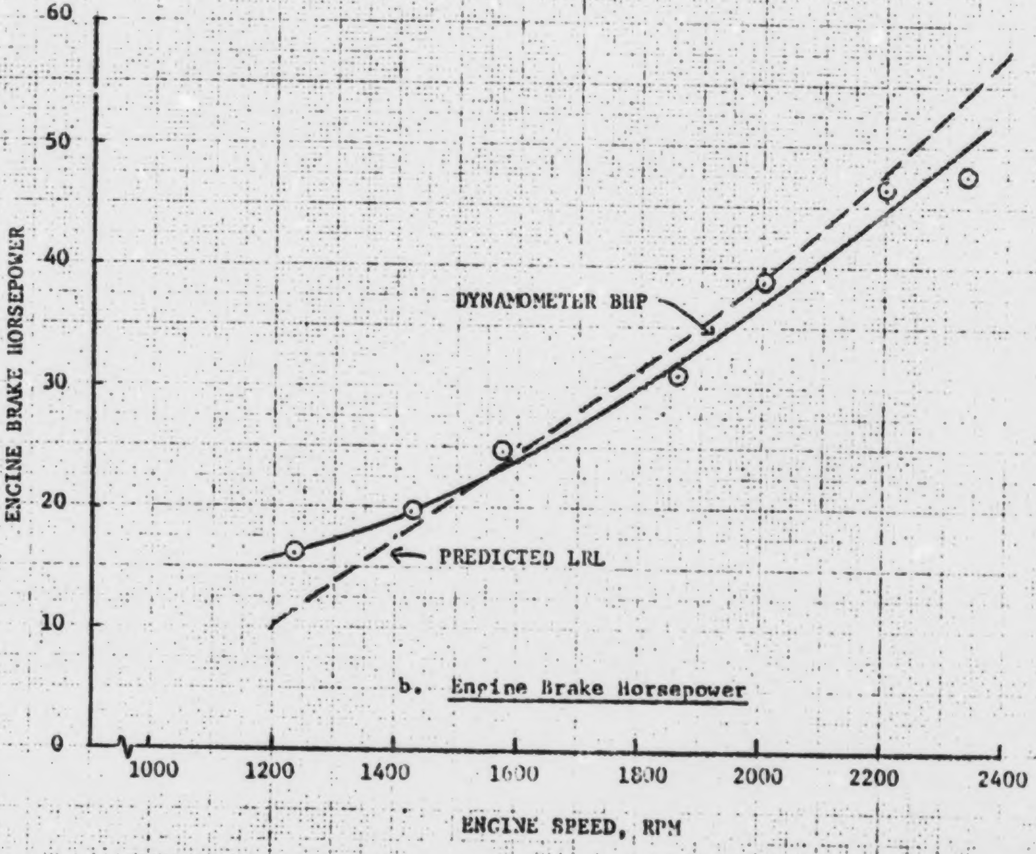
HEC:ei

Enclosures (4)

xc: R. R. Breshears
M. W. Dowdy
G. W. Meisenholder
J. F. Stocky



a. Gasoline Air/Fuel Ratio



b. Engine Brake Horsepower

FIGURE 11. DYNAMOMETER LRL TEST RESULTS FOR CONSTANT $\phi$ AND GASOLINE A/F RATIO

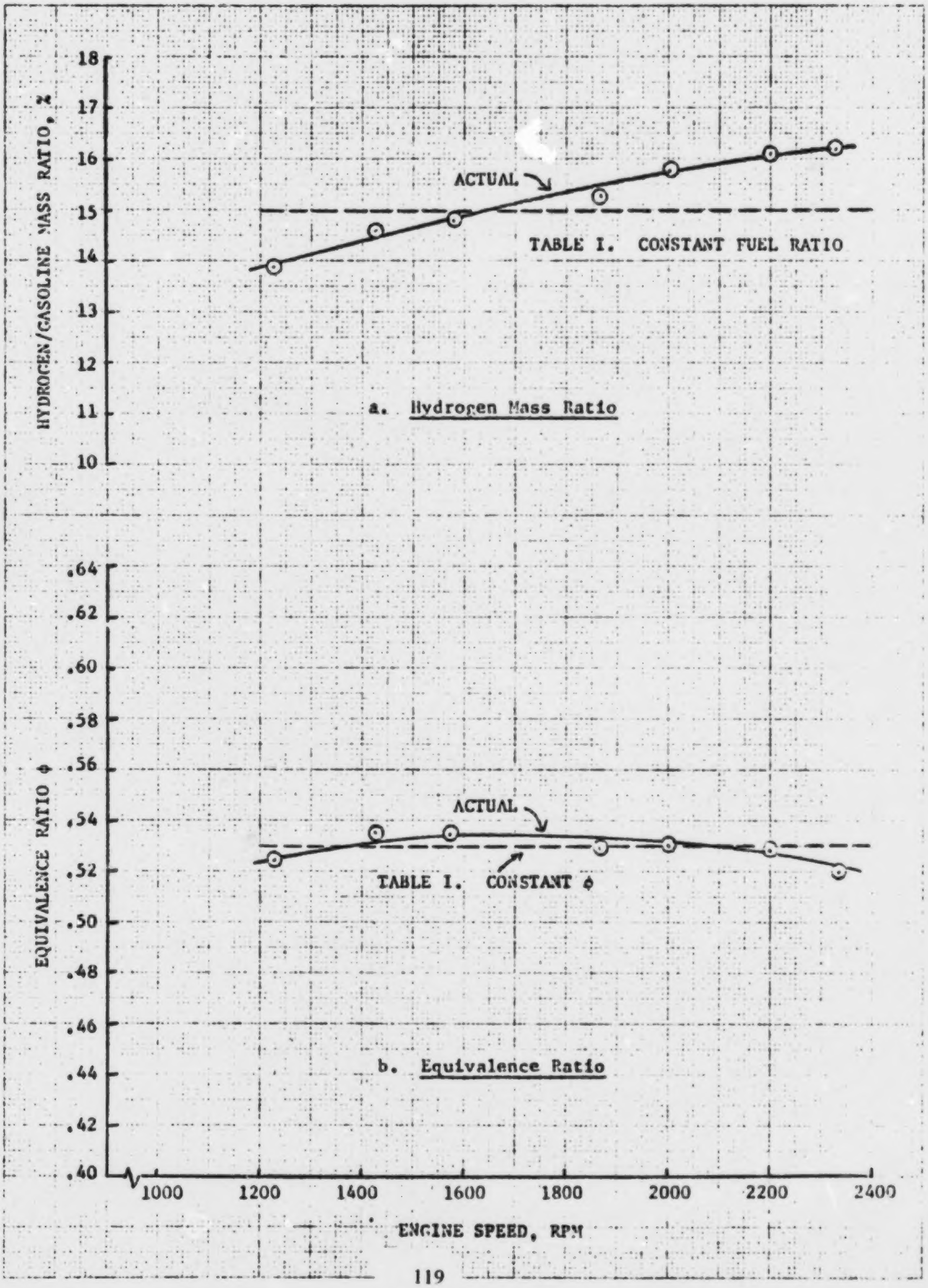
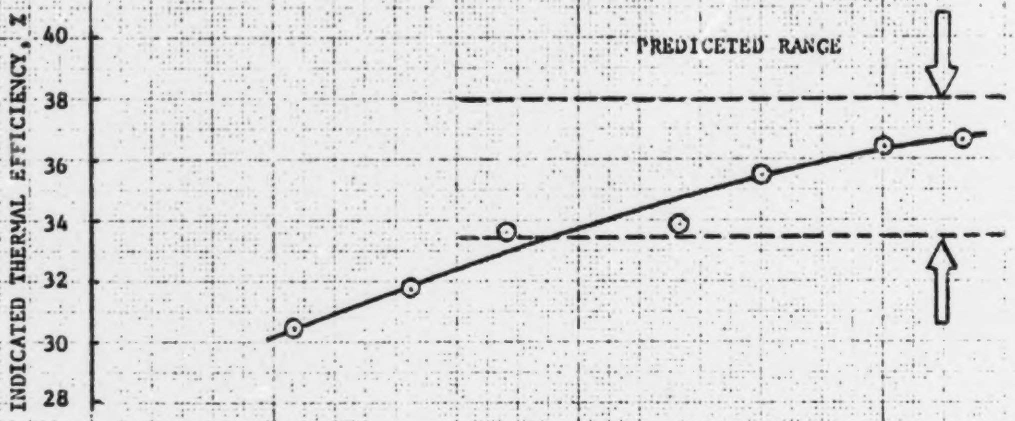
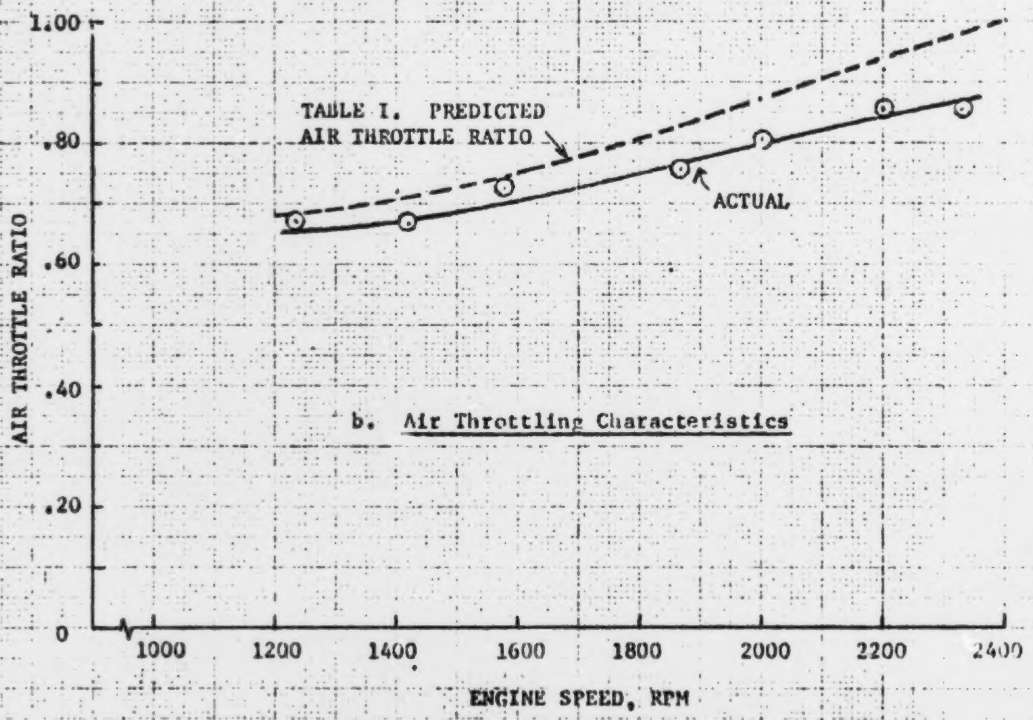


FIGURE 12. DYNAMOMETER LRL TEST RESULTS FOR CONSTANT ϕ AND GASOLINE A/F RATIO



a. Thermal Efficiency



b. Air Throttling Characteristics

FIGURE 13. DYNAMOMETER LRL TEST RESULTS FOR CONSTANT $\phi$ AND GASOLINE A/F RATIO

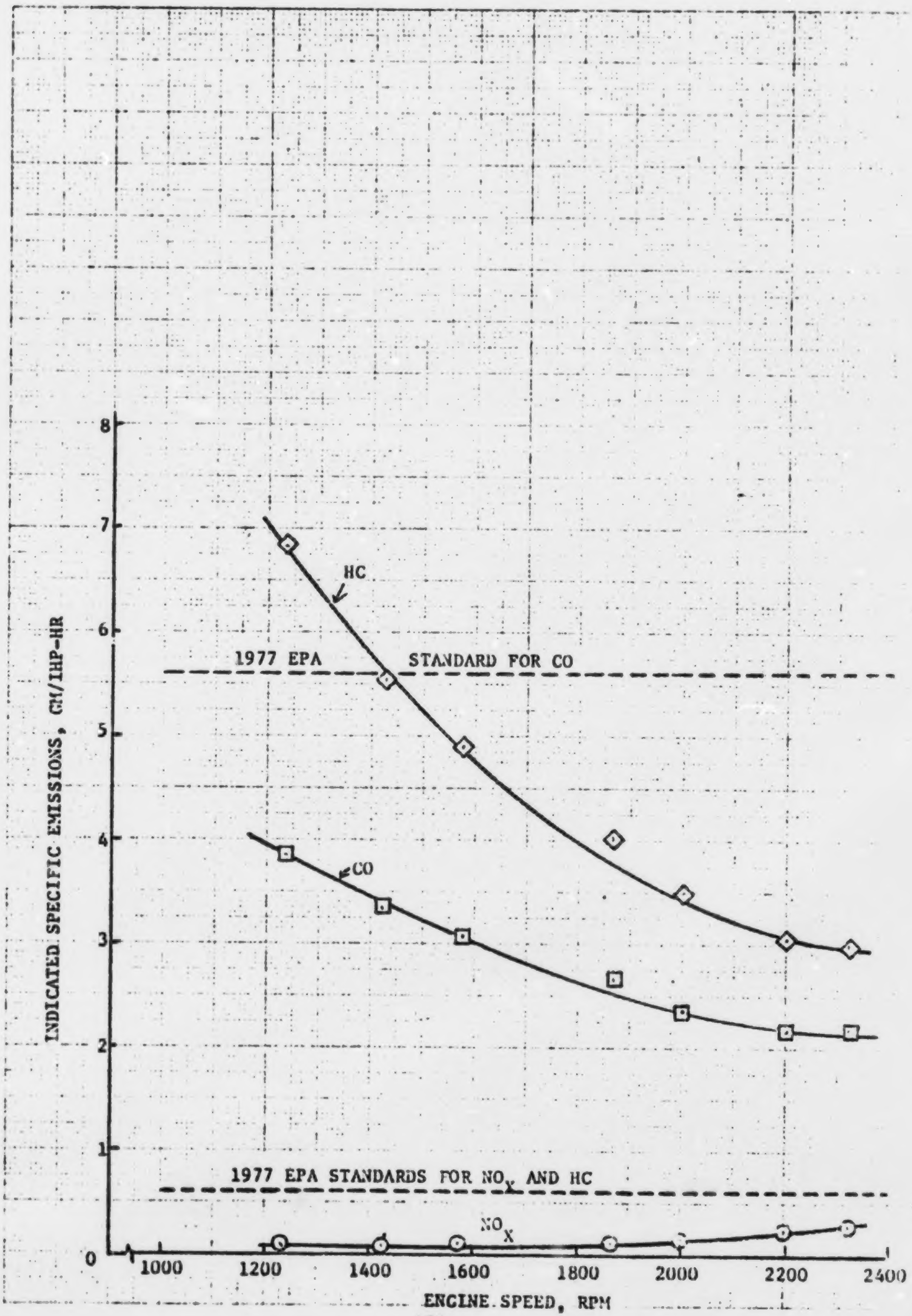


FIGURE 14. DYNAMOMETER LRL EMISSIONS FOR CONSTANT ϕ AND GASOLINE A/F RATIO TESTS WITH MIXED FUELS

**Shell International Petroleum Company Limited**

Shell Centre London SE1 7NA

Telephone
direct line 01-934 4649/2923
switchboard 01-934 1234

Telex
London 919651
Telegraphic Address
Overseas, Shell London SE1
Inland, Shell London Telex

Your ref

VIA AIRMAIL

Scientific Energy Systems Corporation,
570 Pleasant Street,
WATERTOWN,
Mass. 02172,
U.S.A.
Attention: Mr. L.C. Hoagland,
Vice-President and Director of
Research.

Our ref MKR (WN/3)

Date 11th October, 1973.

Dear Sirs,

We should like to thank you for your letter of 18th September regarding the development called "Vapipe". You may be interested to know that the work programme which led to Vapipe arose from our interest in finding that we could run conventional engines at very lean mixture strengths given the right kind of mixture preparation. (You may be familiar with the SAE paper 710588 on this topic).

Our initial efforts on the Vapipe centred around operation in the 19-20/1 air-fuel ratio regime. Partly because of the relaxation on emissions legislation in the U.S.A., we have, for the time being, withdrawn to a regime closer to 17/1, looking at the compromise between emissions reduction, power loss and fuel economy.

While we cannot supply you with sufficiently detailed base information of a type you requested to be of value, we have got fuel consumption measurements made at steady speeds and over standard emission cycles including the 1975 U.S. CVS procedure. These have been included in a presentation to be made to the CCMS Conference on 19th October, 1973 and we enclose a copy for your information.

We should like to point out that the results were obtained in the U.K. from a car originally made for the U.K. market so there are no emission devices built into the vehicle such as ignition retard, EGR, manifold pressure limiter for over-run etc. In addition, the vaporiser on the Vapipe used in the tests was not optimum from a charge temperature or manifold pressure point of view and as a result we were suffering a power loss higher than would be expected from simple mixture strength considerations. However, new developments are in hand which make us optimistic that this unintentional power loss will be eliminated and we therefore anticipate that we can improve on the findings enclosed. As far as the "ultra-lean" i.e. greater than 20/1 air-fuel ratio is concerned, we consider that we are to a great extent limited by the stability of the carburettor metering system employed. All our work has been conducted using standard constant depression carburettors as widely used in the U.K. for many years. A further factor which may well be important in the extent to which the very lean regime is practicable is the high inherent power loss at these ultr-lean mixtures and the extent to which this can be made acceptable. However, given that, we believe that the ultra-lean regime does offer an interesting area for engine operation.

We also enclose a copy of a recent paper on the comparative operation of reciprocating and rotary engines running over a range of mixture strengths which might be relevant to your study.

We trust the enclosed will be of interest and sufficient for the purposes of your study.

Yours truly,
For: SHELL INTERNATIONAL PETROLEUM COMPANY LIMITED

pp: R. LINDSAY

Enclosure

## Opening Statement by W. Robert Price, Jr., Vice President, Corporate Development, Universal Oil Products Company, before the Environmental Protection Agency, Washington, D.C., March 15, 1973[*]

My name is W. Robert Price. I am Vice President of Corporate Development for Universal Oil Products Company. With me are Dr. Vladimir Haensel, Vice President Science and Technology and also a member of the National Academy of Sciences; Dr. Herman S. Bloch, Associate Director of Research; Mr. Ted V. DePalma, Director, Automotive Laboratory and Mr. C. G. Gerhold, formerly with UOP, now retired but serving with us as an independent consultant.

The subpoena with which we were served requested disclosure of progress made in the development and testing of emission control catalysts since last year's hearings. The progress has been in five important areas and has been partly as a result of the open exchange of information and complete cooperation that has existed between us and the automobile companies with whom we have worked.

- Thermal stability.
- Resistance to abuse.
- Lower cost.
- Improved applications technology.
- Three-component control.

In my opening statement I will highlight each of these areas very briefly to serve as a basis for further questioning.

---

[*] See pages 5 and 6.

## THERMAL STABILITY

At last April's hearings, UOP indicated that important improvements had been made in the thermal stability of pelleted catalysts. At that time we had only laboratory data to demonstrate our point although the fact that high temperature shrinkage had been reduced from 40% to 3% indicated we had made a significant improvement. During the past year we have run a number of durability tests on these catalysts with good results. The first four charts in the appendix show HC and CO emission levels over a 50,000 mile period for two of our new stabilized catalysts. The mileage accumulation and test procedure used is described in the schedules preceding these charts. It is a procedure that we follow in order to separate the deterioration due to the catalyst from the deterioration due to the vehicle. We must do this to guide our catalyst research programs. What these tests show is that these two catalysts can handle 50,000 miles of operation within 1975 standards with little if any deterioration on a vehicle that shows little deterioration. But, what about durability on a vehicle that does deteriorate? What about the effects of accidental poisoning?

## RESISTANCE TO ABUSE

The next four charts show the effects of some common vehicle problems such as misfire and high oil consumption and also the effect of contamination with gasoline containing 2.5 grams per gallon of lead. Notice that PZ-217 which showed up well on UOP's standard durability test shows every indication of being within standards when 50,000 miles have been reached in spite of this abuse.

These tests indicate that our new, stabilized catalysts don't need to be pampered. The validity of this observation has been confirmed by the data presented by General Motors on Monday. On Page 11, Section VI, Volume I of their Suspension Request Statement, General Motors lists six different vehicles that completed 50,000 miles in their durability testing program. All six of these used UOP catalysts and five of the six were the new, stabilized version. It is also interesting that on Page 6 of the same section, seven of the catalysts passing the 24,000 mile point were UOP catalysts. Four of these were within 1975 standards at 24,000 miles. The three that failed to meet 1975 standards at 24,000 miles met the standards at 50,000 miles as shown by the data on Page 11.

## LOWER COST

Substantial progress has been made during the year in reducing costs through the more efficient use of noble metals. For example, PZ-236 on which we have demonstrated 50,000 mile durability within 1975 standard levels (see appendix) contains only 450 parts per million of noble metal. In the GM 260 cubic inch underfloor converter, this means 18/1000 T. oz. of a mixture of palladium and platinum at a four to one ratio. At present prices, that is about $1.44 worth of noble metal per car. Noble metals may be exotic as some recent full page ads have been proclaiming but, $1.44 over 50,000 miles is substantially less than the average driver spends for windshield wiper blades. It also makes it hard to reconcile claims that up to three million T. oz. of noble metal per year may be required if catalytic converters are used. The other side of that "up to" coin is that as little as 180,000 T. oz. of noble metal would be required on ten million cars if modern technology is used rather than the older technology that the critics of catalytic emission control are fond of citing. That is only $14,000,000 worth of noble metal imports. Hardly enough to make a dent in the balance of payments picture.

## IMPROVED APPLICATIONS TECHNOLOGY

One of the most important areas of progress has been an increased understanding of how to use catalysts to conserve gasoline mileage. A theory held by some automotive engineers is that emissions should be reduced to a minimum in the engine and that the catalyst should be used as a touchup device. To accomplish this, it is necessary to resort to engine adjustments that impose performance and gasoline mileage penalties. It is apparent from these hearings that some automobile companies have realized the advantage of tuning the engine to perform as it should, using the catalyst to control emissions. When this is done, the mileage and performance penalties ascribed to catalysts disappear. This is not surprising since there is nothing inherent in a properly designed catalytic converter that affects performance or mileage to a significant extent. It has always been and it still is now the attempts to strong-arm the present internal combustion engine into doing things that it doesn't do naturally that have imposed the large mileage and performance penalties falsely attributed to catalysts.

In this regard and looking ahead to the 1976 standards, one of the most important advances of the year may turn out to be the EPA's disclosure that early instruments employed in measuring NOx in ambient air have over stated the presence of this pollutant in most regions. If NOx standards are loosened as a result, it may make it possible to reduce the dependence on exhaust gas recycle and rich air-fuel mixtures to achieve NOx standards. If so, the 30% fuel penalty publicized highly in recent advertisements can be reduced substantially or even eliminated. This fuel penalty is primarily the result of EGR and rich mixtures, not the use of catalysts as is implied.

## THREE-COMPONENT CONTROL

In their February 15 report, the National Academy of Sciences recognized the advantages of a system in which all three principal pollutants are controlled in a single catalyst bed. A primary concern has been a lack of information on the durability of catalysts having three-component control capability. Recent work at UOP has shown that after 50,000 miles of service, PZ-236 retains the ability to reduce NOx by 55% when operated on stoichiometric air-fuel mixtures. This is the same catalyst referred to earlier that went 50,000 miles within 1975 standards on $1.44 worth of noble metal.

A problem still remaining is how to maintain a stoichiometric mixture in all modes of vehicle operation. However, improvements in carburetion and recent improvements in oxygen sensor design indicate that more rapid advances in this attractive system may be possible in the near future.

We feel that this development needs a lot more attention than it has been getting since it offers the public the advantages of a self tuning car capable of delivering performance and gasoline mileage that have not been seen for many years.

## CONCLUSION

A conclusion that can be drawn as a result of recent advances in the development of emission control catalysts is that much of the strident criticism of the use of catalysts is really directed at their misuse and at the mechanical gadgets and engine adjustments employed to make them less necessary. Far from being a waster of the nation's energy resources, catalysts may be the most potent energy conservation tool available at the present time that is also compatible with reasonable clean air objectives. Far from being a foe, catalysts may be Detroit's best friend -- making it possible once again to produce automobiles that run right while still controlling emissions.

# \# \#

# APPENDIX

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## TEST OBJECTIVES:

The objective of the 50,000 mile durability tests which are described in the attached graph was to determine any change which might occur in the activity of the catalyst. The procedure used was such that the deterioration due to loss of catalytic activity was separated from deterioration due to the vehicle.

## TEST PROCEDURE:

In all tests the catalyst-converter system was aged on the latest model vehicle obtainable. The ageing vehicle was initially tuned to factory specifications and maintained to good performance standards thereafter. No changes were made to the engine.

Ageing was performed about half of the time on a chassis dynamometer with the balance being done on the road. The ageing schedules are appended along with the fuel and lubricant analyses.

At periodic intervals the catalyst-converter system was removed from the ageing vehicle and performance tested on a base car which was maintained to reasonably constant base emission levels. The base car was also a standard vehicle with no changes made to it. Since it was used for 1975 CVS testing only, the vehicle variability over the 50,000 miles was limited to a low level.

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# AGEING SCHEDULES

## Road Ageing Lap

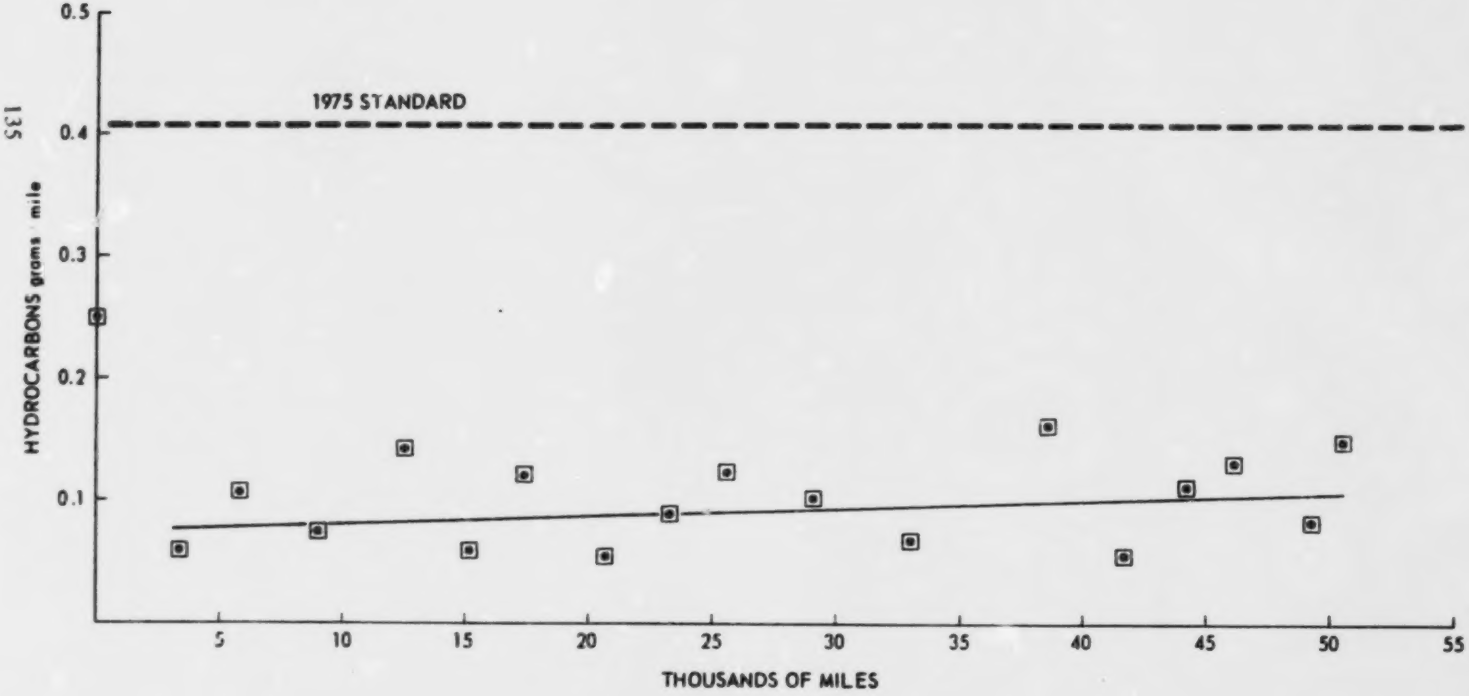
| | |
|---|---|
| Total Average Miles Per Lap | 48 Miles |
| Total Average Time Per Lap | 1.33 Hours |
| Average Speed Per Lap | 36 MPH |
| Maximum Speed | ~75 MPH |

## 13-Mode Dynamometer Ageing Cycle

| Mode | Mode Time | Total Time |
|---|---|---|
| Idle | 15 Sec. | 15 Sec. |
| I - 37.5 MPH | 14 Sec. | 29 Sec. |
| 37.5 MPH Cruise | 13 Sec. | 42 Sec. |
| 37.5 MPH - 18.75 MPH | 11 Sec. | 53 Sec. |
| 18.75 MPH - 50 MPH | 21 Sec. | 74 Sec. |
| 50 MPH Cruise | 44 Sec. | 118 Sec. |
| 50 MPH - 25 MPH | 17 Sec. | 135 Sec. |
| 25 MPH Cruise | 10 Sec. | 145 Sec. |
| 25 MPH - I | 8 Sec. | 153 Sec. |
| Idle | 10 Sec. | 163 Sec. |
| I - 62.5 MPH | 17 Sec. | 180 Sec. |
| 62.5 MPH Cruise | 40 Sec. | 220 Sec. |
| 62.5 MPH - I | 20 Sec. | 240 Sec. |

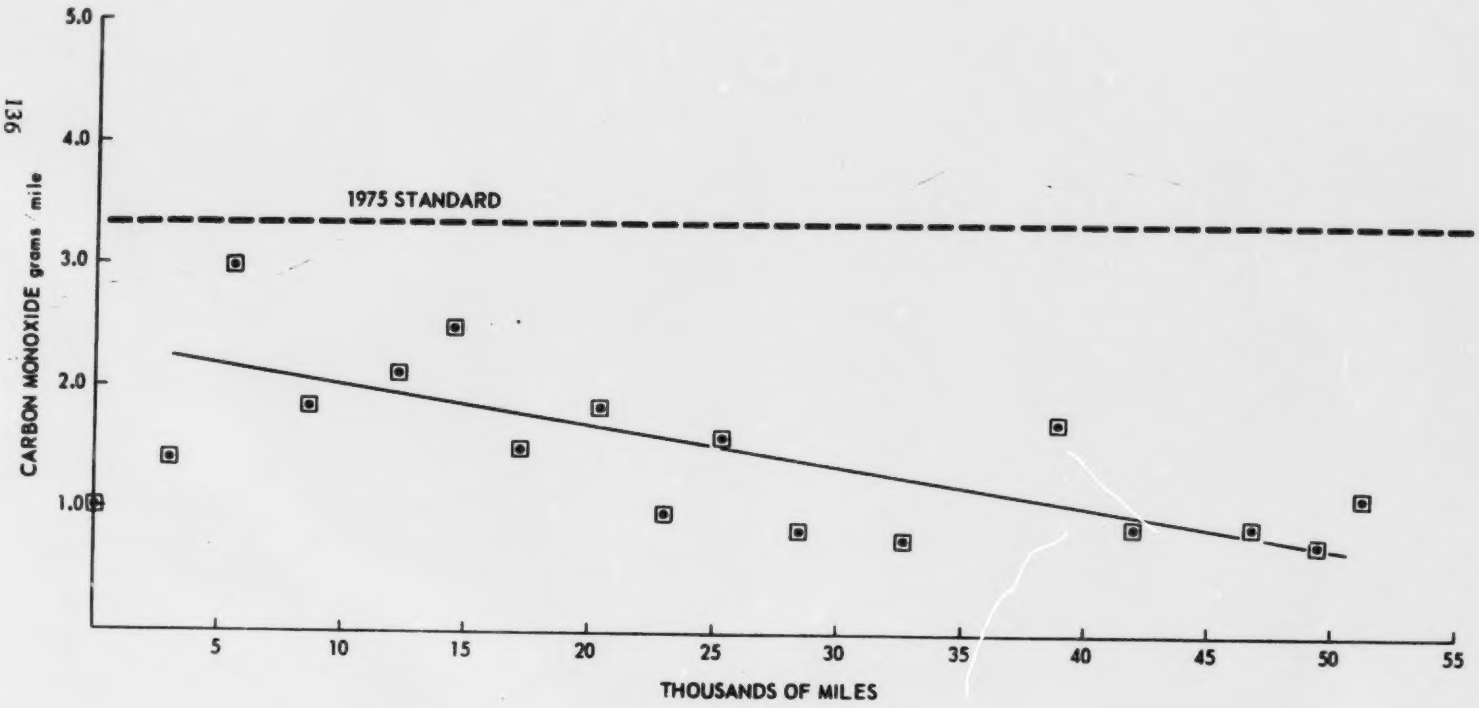
## STANDARD DURABILITY TEST
## PELLETED NOBLE METAL CATALYST
## HYDROCARBON EMISSIONS vs MILES

PZ-217
260 in$^3$ Converter
2.24 grams Total Metals
Test Car: 1971 Chevrolet, 350 CID with AIR
Mileage Acumulation Test Car: 1972 Chevrolet, 350 CID



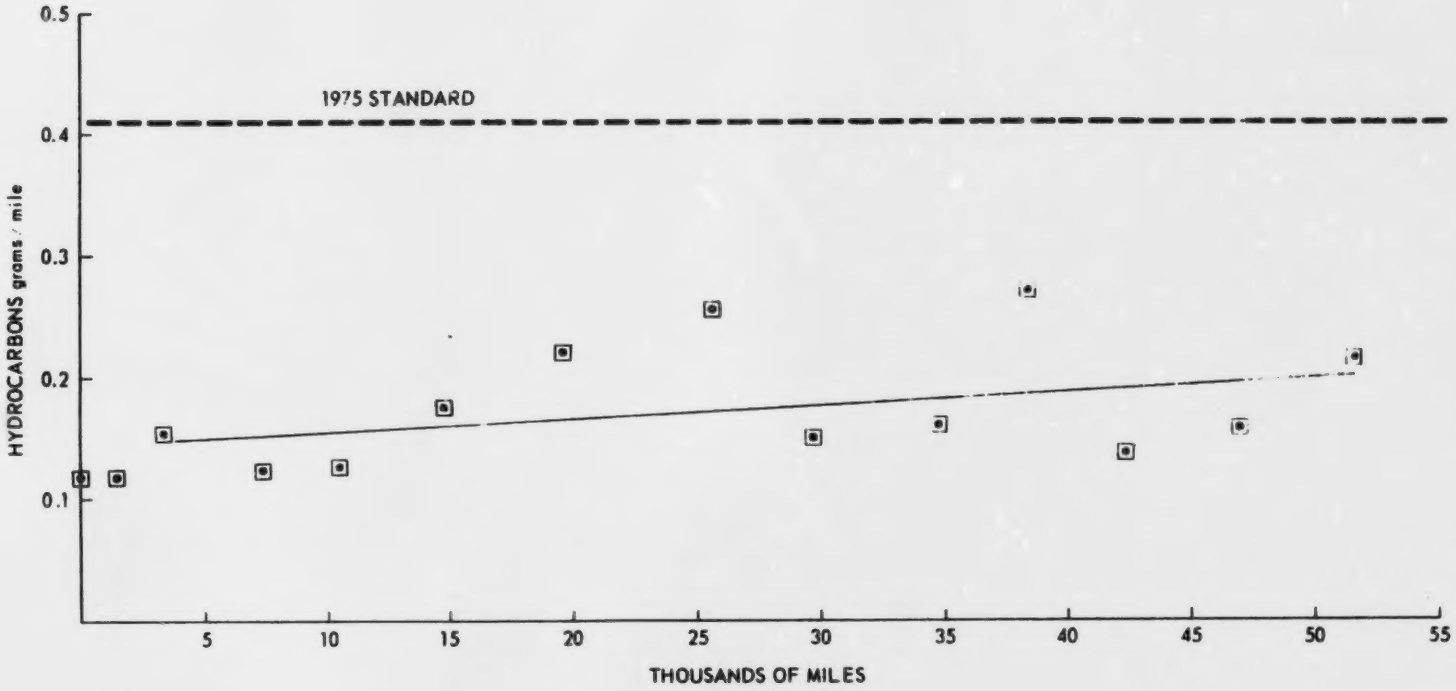
### STANDARD DURABILITY TEST
### PELLETED NOBLE METAL CATALYST
### CARBON MONOXIDE EMISSIONS vs MILES

PZ-217
260 $in^3$ Converter
2.24 grams Total Metals
Test Car: 1971 Chevrolet, 350 CID with AIR
Mileage Acumulation Test Car: 1972 Chevrolet, 350 CID



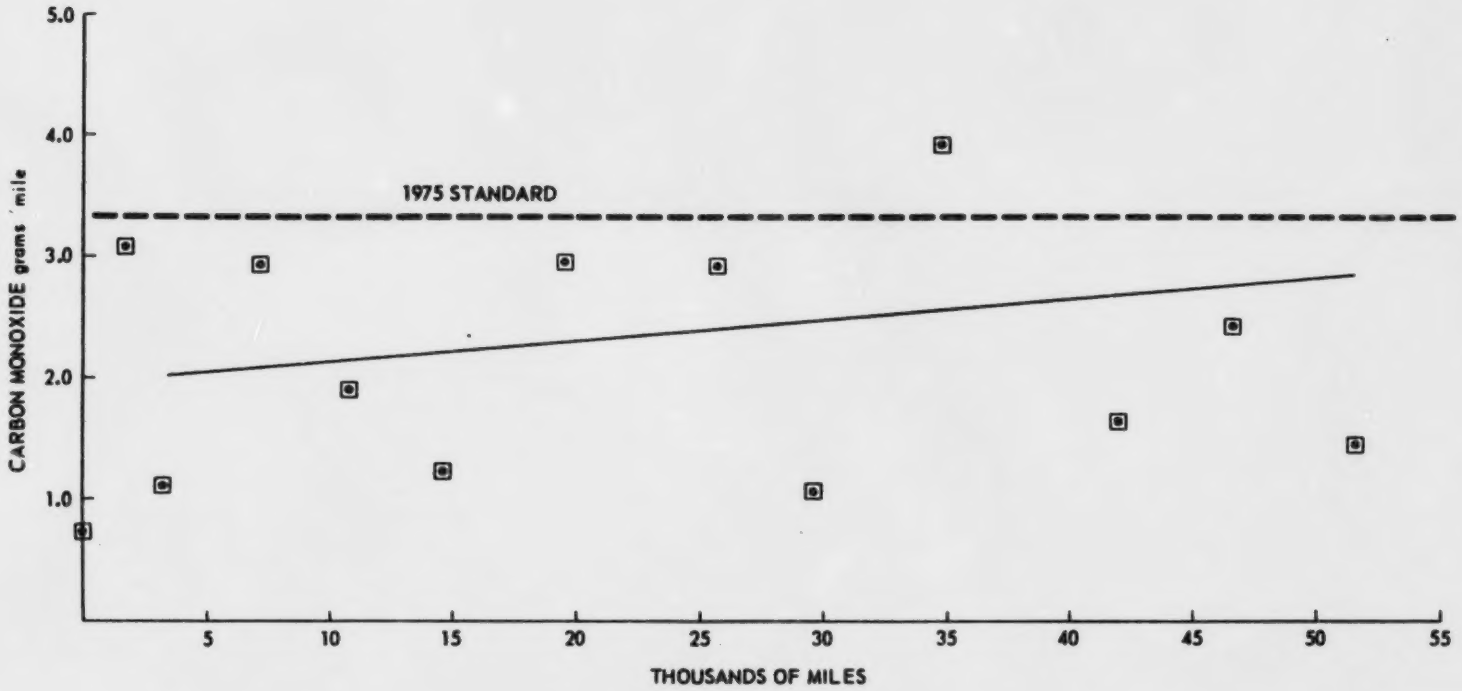
## STANDARD DURABILITY TEST
## PELLETED NOBLE METAL CATALYST
## HYDROCARBON EMISSIONS vs MILES

PZ-236
260 in³ Converter
0.56 grams Total Metals
Test Car: 1971 Chevrolet, 350 CID with AIR
Mileage Acumulation Test Car: 1971 FORD, 351 CID



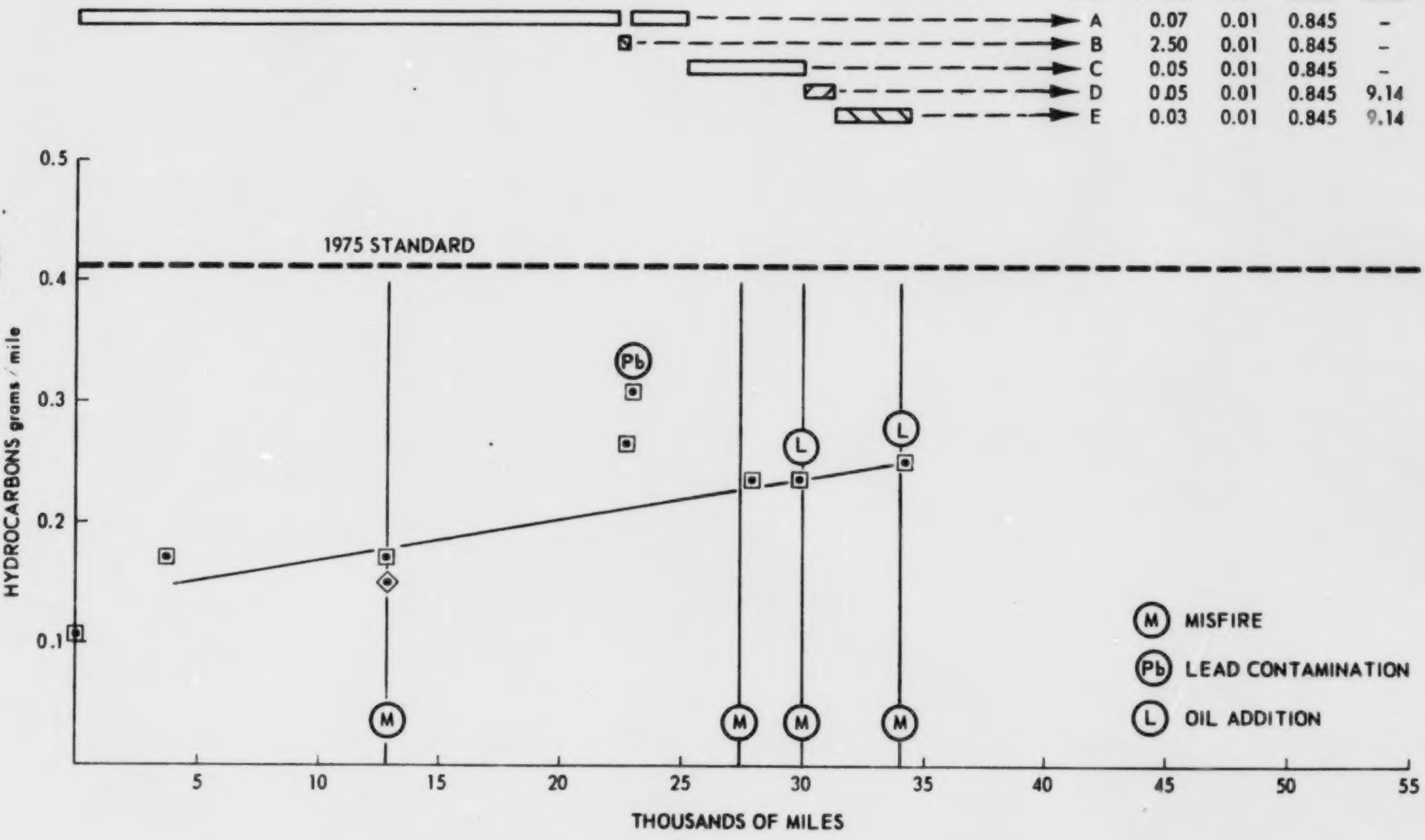
## STANDARD DURABILITY TEST
## PELLETED NOBLE METAL CATALYST
## CARBON MONOXIDE EMISSIONS vs MILES

PZ-236
260 in$^3$ Converter
0.56 grams Total Metals
Test Car: 1971 Chevrolet, 350 CID with AIR
Mileage Acumulation Test Car: 1971 FORD, 351 CID



## ABUSE DURABILITY TEST
## PELLETED NOBLE METAL CATALYST
## HYDROCARBON EMISSIONS vs MILES

PZ-217-1
260 in³ Converter
2.24 grams Total Metals
Test Car: 1971 Chevrolet, 350 CID with AIR
Mileage Acumulation Test Car: 1973 Chevrolet, 350 CID

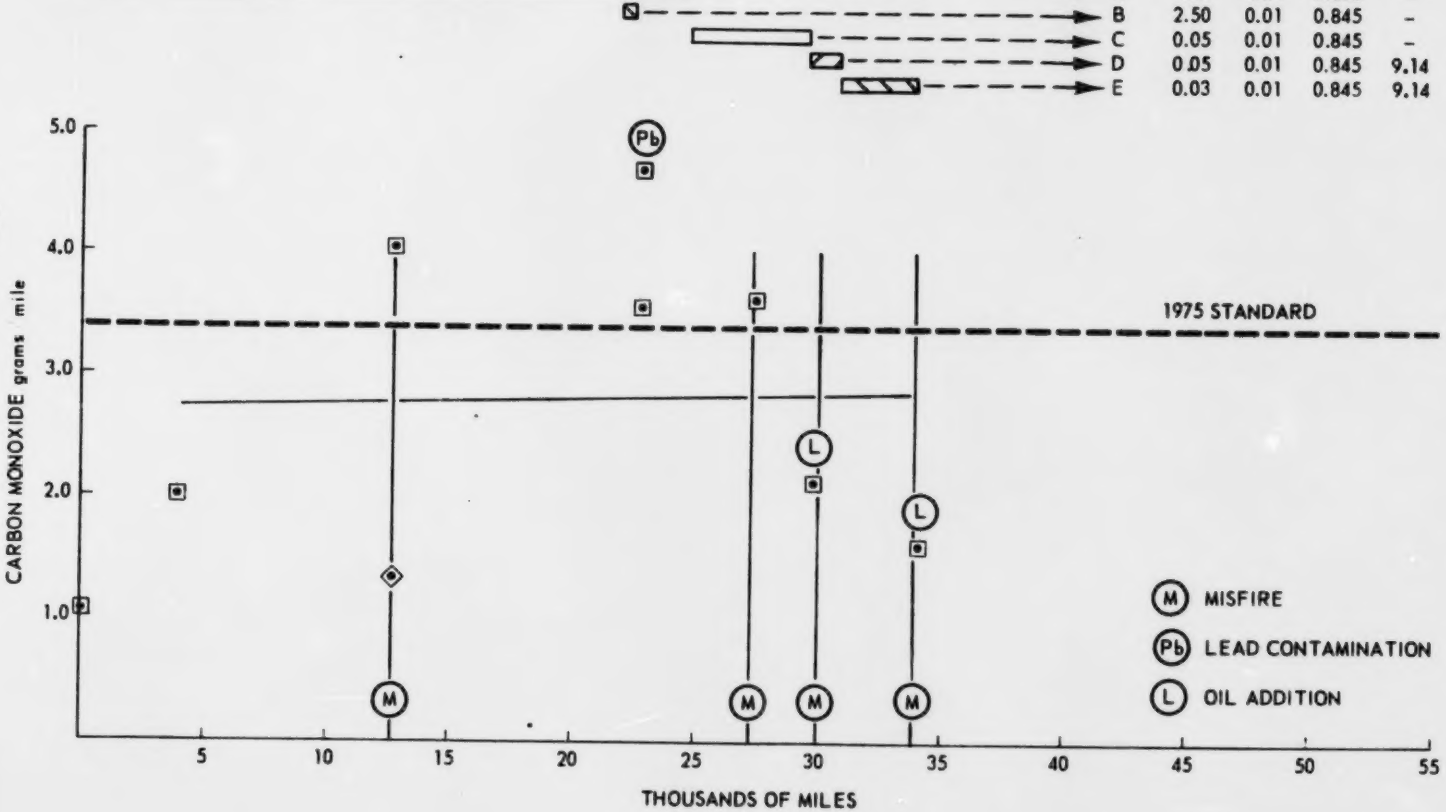


CONTAMINANTS grams / gallon

| Fuel | Pb | P | S | Oil |
|---|---|---|---|---|
| A | 0.07 | 0.01 | 0.845 | – |
| B | 2.50 | 0.01 | 0.845 | – |
| C | 0.05 | 0.01 | 0.845 | – |
| D | 0.05 | 0.01 | 0.845 | 9.14 |
| E | 0.03 | 0.01 | 0.845 | 9.14 |

## ABUSE DURABILITY TEST
## PELLETED NOBLE METAL CATALYST
## CARBON MONOXIDE EMISSIONS vs MILES

PZ-217-1
260 in$^3$ Converter
2.24 grams Total Metals
Test Car: 1971 Chevrolet, 350 CID with AIR
Mileage Acumulation Test Car: 1973 Chevrolet, 350 CID



CONTAMINANTS grams/gallon

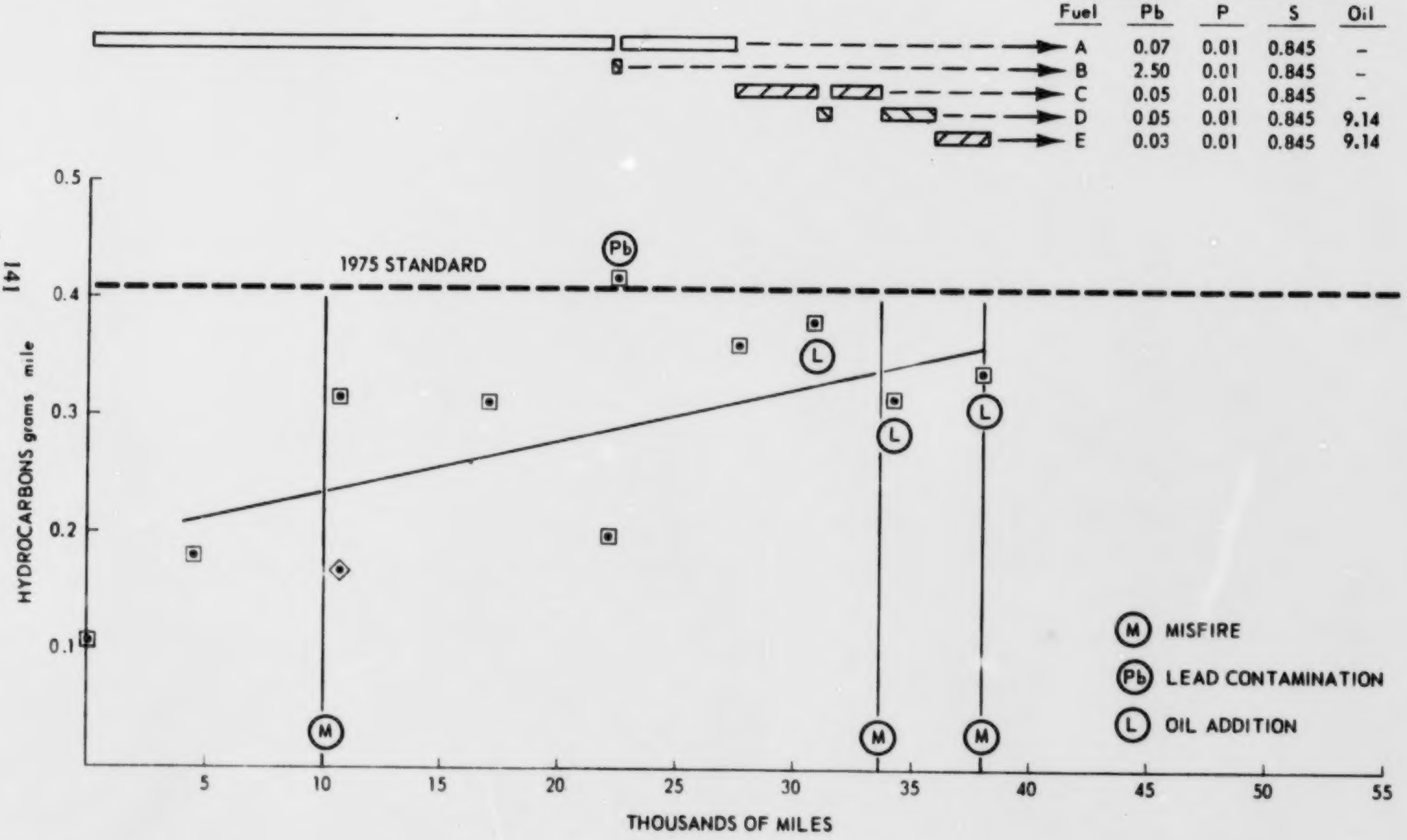
| Fuel | Pb | P | S | Oil |
|---|---|---|---|---|
| A | 0.07 | 0.01 | 0.845 | – |
| B | 2.50 | 0.01 | 0.845 | – |
| C | 0.05 | 0.01 | 0.845 | – |
| D | 0.05 | 0.01 | 0.845 | 9.14 |
| E | 0.03 | 0.01 | 0.845 | 9.14 |

# ABUSE DURABILITY TEST
# PELLETED NOBLE METAL CATALYST
# HYDROCARBON EMISSIONS vs MILES

PZ - 255 - 2
260 in$^3$ Converter
1.56 grams Total Metals
Test Car: 1971 Chevrolet, 350 CID with AIR
Mileage Acumulation Test Car: 1973 Chevrolet, 350 CID

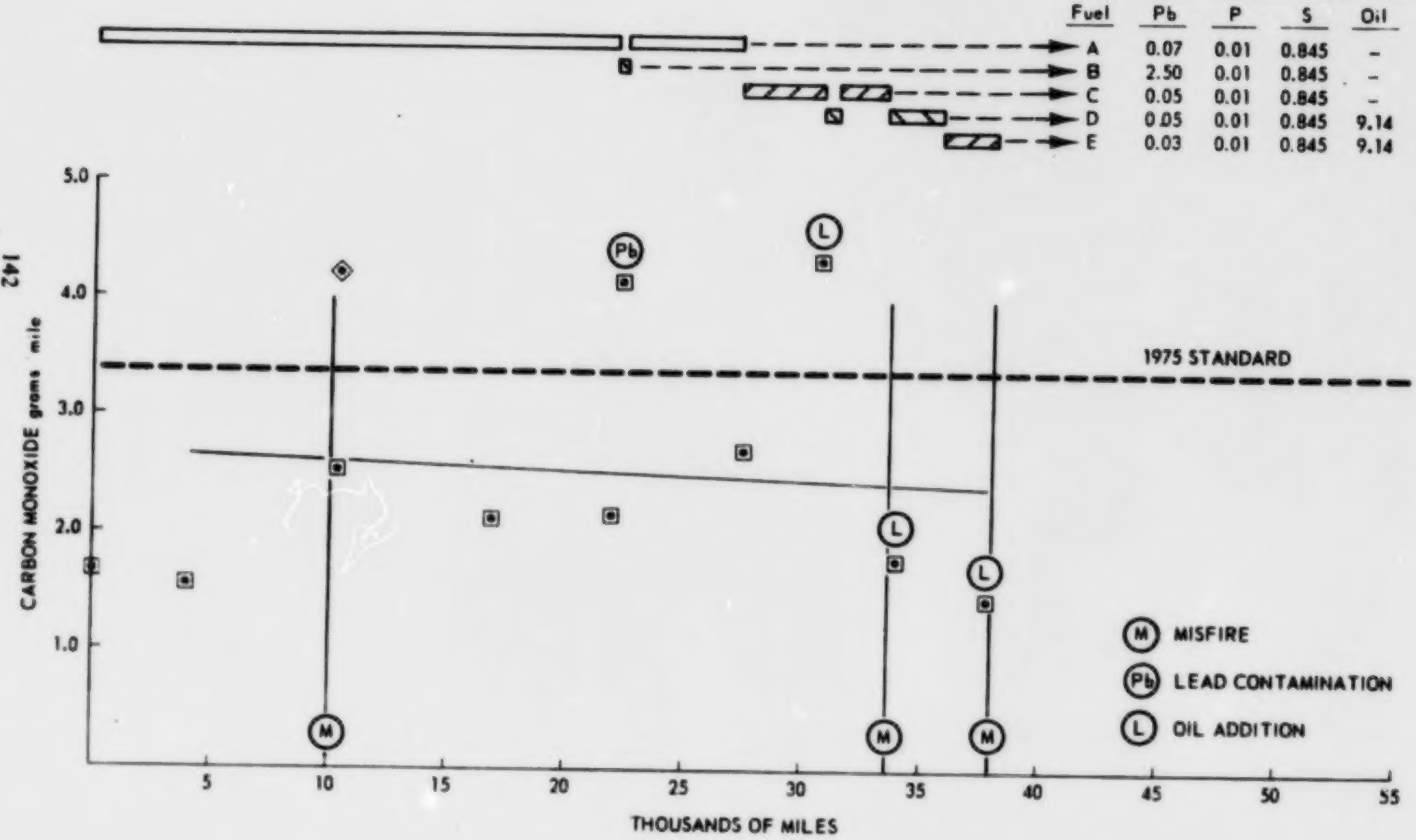
CONTAMINANTS grams/gallon

| Fuel | Pb | P | S | Oil |
|---|---|---|---|---|
| A | 0.07 | 0.01 | 0.845 | – |
| B | 2.50 | 0.01 | 0.845 | – |
| C | 0.05 | 0.01 | 0.845 | – |
| D | 0.05 | 0.01 | 0.845 | 9.14 |
| E | 0.03 | 0.01 | 0.845 | 9.14 |



# ABUSE DURABILITY TEST
# PELLETED NOBLE METAL CATALYST
# CARBON MONOXIDE EMISSIONS vs MILES

PZ-255-2
260 in$^3$ Converter
1.56 grams Total Metals
Test Car: 1971 Chevrolet, 350 CID with AIR
Mileage Acumulation Test Car: 1973 Chevrolet, 350 CID



CONTAMINANTS grams / gallon

| Fuel | Pb | P | S | Oil |
|---|---|---|---|---|
| A | 0.07 | 0.01 | 0.845 | – |
| B | 2.50 | 0.01 | 0.845 | – |
| C | 0.05 | 0.01 | 0.845 | – |
| D | 0.05 | 0.01 | 0.845 | 9.14 |
| E | 0.03 | 0.01 | 0.845 | 9.14 |

# STATEMENT BY W. ROBERT PRICE, JR., VICE PRESIDENT, UNIVERSAL OIL PRODUCTS COMPANY, BEFORE A PUBLIC HEARING OF THE UNITED STATES ENVIRONMENTAL PROTECTION AGENCY RELATIVE TO A DELAY OF THE 1976 FEDERAL AUTOMOTIVE EMISSION CONTROL STANDARDS

We are pleased to respond to the EPA's request that we testify as to Universal Oil Products Company's conclusions on the feasibility of meeting the exhaust emission standards required by the 1970 Clean Air Act for 1976 automobiles. Our conclusions and our comments on important related matters are as follows. We will expand briefly on each of these statements and conclusions in the balance of our opening statement.

1. We are not aware of any technology presently available by which the 1976 NOx standard can be met on 1976 model cars.

2. If maximum NOx control, as reflected by the present 1976 standard, continues to be required, we believe that a three-component control system using a single catalyst bed and feedback control of air/fuel ratio provides the most feasible and economical near-term solution.

3. UOP wants to emphasize that the NOx standard is the primary determinant of the costs and penalties of emission control systems. Prompt action in establishing the level of this standard is needed to give the proper direction to research and development programs that are costing American industry hundreds of millions of dollars per year. Establishment of a final standard for NOx will put an end to the speculation concerning the possible cost to the motorist and the Nation of emission control. Recommendations as to the best way of achieving Clean Air Standards would change drastically if a NOx standard in the range of 3.1 to 1.5 grams per mile were to be established. Within this range, efficient, single-bed, oxidizing catalysts are the key to designing emission control systems that not only reduce emissions to lower levels than possible in today's cars but lead to better performance and gasoline economy as well.

4. Maximum utilization of petroleum energy resources is compatible with the use of single bed, oxidizing catalysts in systems designed to meet a 3.1 grams per mile NOx standard or in systems designed for lower NOx levels, provided three-component catalysts are used rather than dual-bed catalysts. With either of these systems, gasoline energy policy should be directed to making an unleaded gasoline pool having a Research Octane Number of about 96 available on a National basis. This will maximize efficiency of energy utilization and minimize the amount of crude petroleum required to fill the needs of the motoring public.

Referring now to our first conclusion, we are not aware of the existance of technology that can make it possible to achieve the 1976 standards on 1976 model automobiles within the provisions of the Clean Air Act. Our Research and Development Program has concentrated on two different catalytic approaches. One was concentrated on reducing catalysts for use in dual-bed systems and the other on the development of three-component control catalysts and systems. Although we have never felt that the dual-bed catalyst system had the potential of the three-component control system, we have had to devote substantial resources to it since our customers were required to show due diligence in trying to meet the 1976 standards and we had to devote a substantial effort to the development of reducing catalysts to support their needs.

Our search for acceptable reducing catalysts for NOx conversion has included work on base metal catalysts, noble metal catalysts and noble metal/ base metal combinations, all on both pellet and monolithic supports. About one thousand reducing catalysts have been made and tested in our laboratories and about three hundred of these were evaluated on test stand dynamometers. We have found noble metal catalysts that can control NOx in laboratory tests to the levels required for 1976. However, the durability indicated for these catalysts has been so poor that we have not even felt it worthwhile to run vehicle durability tests.

UOP believes that three-component control systems are far more promising than dual-bed catalyst systems. Laboratory test data shows NOx reductions of 80% to 90% are consistently available on well designed, three-way catalysts. This is adequate to achieve NOx emissions at about the levels required by the 1976 standards. Work completed in May by the Bartlesville Energy Research Center of the Bureau of Mines confirms some of our observations. They have generously authorized us to refer to this work in our testimony. Steady state tests conducted by them on a UOP three-way control catalyst at 60 mph road load showed conversions of NOx as high as 93% when air/fuel ratios were accurately controlled.

Although all of these indications are favorable, we don't have hard vehicle durability data since the other essential elements of a practical three-component control system have not been developed. However, we would expect durability to be equivalent to that achieved with our thermally stabilized, oxidizing catalysts for two reasons. First, the compositions are very similar. Second, NOx conversion tests run on catalyst aged for 50,000 miles showed very little deterioration from fresh catalyst.

Three-component control systems are based on the well established fact that if the air/fuel ratio is maintained at the stoichiometric ratio, about 14.7 to 1, the composition of the exhaust gases leaving the engine will be such that a single bed catalyst can be used to simultaneously eliminate all three pollutants. Using present types of carburetion, the only way known of maintaining this air/ fuel ratio through all engine operating modes is through the use of a feedback control loop. A sensor in the exhaust line is used to analyze exhaust gas composition continuously and feed information back to the carburetor concerning corrections needed to maintain the stoichiometric ratio.

The sensor is the weak link in present three-component control systems since durability is still a problem. However, the technological gap remaining to be closed to develop a mass producable sensor is at least as small as that remaining to develop a reducing catalyst having satisfactory durability. Moreover, since the sensor should be a simple device costing not much more than a spark plug, it is possible that it could be replaced at regular intervals if necessary.

Since an air/fuel ratio of 14.7 to 1 is between the points of maximum performance and maximum economy, it provides a good combination of both. The feedback control loop, by maintaining stoichiometry, would keep the vehicle in constant tune regardless of operating mode, temperature, humidity, altitude or fuel composition. The benefits of such a system to the motoring public are substantial enough so that even if emission control were not a factor, higher fuel prices, factors relating to utilization of national energy resources and competition would probably lead to the use of feedback control systems on increasingly large numbers of cars in the future.

So much for the No NOx systems as we sometimes refer to systems designed to meet the 1976 NOx standard. In my opening remarks I emphasized that the level of the NOx standard determines the costs and penalties of emission control systems. If NOx levels of 3.1 grams per mile are found to be adequate, the simple, inexpensive, single bed, oxidizing catalyst systems that are available now can be used. When catalysts are used to control emissions to this level, they can take the pollution control burden off of the engine, making it possible to tune it to regain virtually all of the mileage and performance penalties lost over the years through adjusting the engine to control emissions instead of run efficiently. The use of catalysts makes it possible to advance the spark and eliminate or nearly eliminate exhaust gas recycle (EGR), both of which have been responsible for an important part of the mileage and performance penalties imposed over the years by non-catalytic emission control systems.

As NOx levels lower than 3.1 grams per mile are specified, two different approaches may be used. One approach involves the use of increasing amounts of EGR, with some fuel and performance penalties. Spark retard, imposing more penalties, would have to be added as NOx levels approaching 1.5 grams per mile are required. Different makes and models of cars, differ in the extent to which EGR and spark retard is needed.

Another approach would involve the use of improved carburetion to maintain the air/fuel ratio closer to stoichiometric more of the time. As mentioned previously, a single catalyst bed will reduce NOx as well as HC and CO during the periods that the stoichiometric air/fuel ratio is maintained. Increasing the amount of time that the air/fuel ratio is passing through stoichiometric will add significant NOx reduction.*

As NOx levels much below 1.5 grams per mile are needed, three-component control or dual-bed catalyst systems will be necessary.

Moving now to our final point, we would like to emphasize that the NOx standard chosen and the emission control system used to meet it will have an important effect on the efficiency with which our Nation's petroleum energy resources are used. The adoption of dual-bed catalyst systems would be wasteful. The use of three-component control systems or revising the NOx standard to the 1975 interim standard level so that simple oxidizing catalyst systems can be used would conserve energy in comparison with present 1973 automobile emission control systems. Both of these systems will require the use of unleaded fuel. Contrary to some claims, the use of unleaded fuel does not lead to less efficient utilization of petroleum energy.

It has been said frequently that 4% more crude petroleum must be processed to produce unleaded fuel than leaded fuel. This is true, but it should be added that this additional 4% crude usage does not mean a 4% energy loss. It merely means that in the course of refining, the 4% has been converted to products other than gasoline, in this case largely substitute natural gas. It has also been pointed out that the additional refining cost to produce a lead-free gasoline pool is in the range of 1 1/2¢ per gallon. However, studies by petroleum companies and automobile companies alike have shown that the motorist will save as much as 4¢ to 5¢ per gallon in maintenance. These two factors show that there will be a net savings to the use of lead-free gasoline and from the National standpoint, there will be no energy loss.

In addition, UOP studies show that a significant improvement in energy utilization is possible if an unleaded gasoline pool having a Research Octane Number of about 96 is provided. This will enable automobile manufacturers to return to the use of higher compression ratio engines with the attendant improvement in engine efficiency.

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*This is not necessarily feedback control.

Before concluding my remarks, I would like to comment on two items recently appearing in the press that have implied the possibility of toxic emissions from catalytic converters. The most recent, questioned the possible toxic effects of metal particles from catalytic converters. With regard to this, the catalysts UOP is now planning to manufacture for automotive use do not contain either chromium or nickel. With regard to platinum or palladium, there is no known toxic effect due to particles of these metals. Further, the level of emissions of these metals over a 50,000 mile period from a typical UOP catalyst is less than one part per ten billion parts of exhaust. It's interesting to note that lead emissions in the exhaust of a vehicle using conventional leaded fuel are fifty thousand times as high as this. And, lead is known to be toxic.

The other article referred to possible carcinogenic emissions. With regard to this, catalytic converters have been found to be 95% effective in removing polynuclear aromatic hydrocarbon (PNAH) tars from automobile exhaust. Typical automobile exhaust emits about ten milligrams of these tars in one hour. This compares to eighteen milligrams contained in the smoke from one cigarette. After passing through a catalytic converter, the same amount of exhaust would contain only 0.5 milligrams of tar. This means that all of the exhaust from a vehicle equipped with a catalytic converter would have to be inhaled for 36 hours before exposing the body to the same amount of tar contained in one cigarette.

Thank you gentlemen. We invite your questions.

## THREE COMPONENT CONTROL USING AUTOMATIC SELF-TUNING ENGINE

The most hopeful approach to meeting the 1976 standards lies in the combination of a self-tuning engine and a catalytic converter for the simultaneous catalytic control of all three of the principal pollutants. This type of approach depends on the fact that there is a very narrow composition window at which the oxidation reactions which are necessary for the destruction of carbon monoxide and hydrocarbons and the reduction reactions which are necessary for the reduction of nitrogen oxide are essentially balanced. If the composition of the exhaust gases going to the catalyst is held with sufficient precision (within about one percent) in the vicinity of this optimum zone, catalytic treatment will result in very high simultaneous destruction of all three of the pollutants.

The principal problem in connection with this type of operation is the maintenance of the composition of the exhaust gas within these very tight specifications through a variety of driving modes and engine and environmental conditions. However, a great deal of progress has been and is continuing to be made in achieving this type of an automatic self-tuning engine, employing a closed loop feed-back mechanism. This type of system depends on a very sensitive, rapid, automatic continuous sensing of the composition of the exhaust gases leaving the catalytic converter. Sensor output is used to continuously adjust the relative air-fuel inputs to maintain the composition at the optimum level in each vehicle at all times.

UOP has under development a very rapid, simple sensing device, with no moving parts, which is capable of continuously monitoring the oxygen concentrations at low levels to a very high precision, and producing an electrical signal proportional to the concentration. They are also developing servo mechanisms using the signal from this sensor, by continuous adjustment of the ratio of air to fuel to the engine, to hold the oxygen concentration within the desired limits. It is believed that sufficiently concentrated effort put behind this activity would make possible the development of workable systems in time for use on 1976 model vehicles.

Aside from the practicability of meeting or exceeding 1976 standards inherent in this approach, this system also has a number of other very important advantages. Probably the most important of these is that the engine is held very nearly at stoichiometry and, as a result, the very serious performance and fuel penalties which characterize all alternative approaches to nitrogen oxide elimination are not experienced. A stoichiometric engine operating condition is very nearly maximum economy.

The system should also eliminate a great many of the problems between individual vehicles which result from inherent variability due to various manufacturing tolerances. The self-tuning engine will make the proper adjustments to exactly compensate for these variations and, therefore, will produce the same quality of exhaust gas from each engine.

For similar reasons, operational variabilities which result from variations in customer driving habits, fuel composition, atmospheric conditions, altitude, and induction system deterioration will be automatically noted and exactly compensated for.

One of the principal causes of failure in catalytic converter systems is excessive temperature caused by the simultaneous presence of large amounts of combustibles and oxygen which result from the combination of a rich operating engine and an excess of secondary air. The self-tuning engine operation, however, does not require secondary air and, as such, this potentially destructive combination is impossible to attain.

The system is, however, in common with all other oxidative systems, susceptible to high temperatures in the event of serious sustained ignition failure since, in this case, the burning of a large part of the stoichiometric mixture takes place in the catalyst rather than in the engine.

As a general matter, the self-tuning engine - catalytic converter is much more nearly a fail-safe system than other nitrogen oxide control systems that have been proposed. In the event that the control system fails, the result will be that the engine will either run considerably richer or leaner than stoichiometry with the result that the individual operator will experience a serious loss of performance and will be, therefore, encouraged to take his vehicle to the shop for immediate repair. This is in marked contrast to systems such as exhaust gas recycle in which a failure will be accompanied by a better performance of the vehicle and the customer will be reluctant to arrange for the proper repairs.

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# SUPPLEMENTAL INFORMATION IN CONNECTION WITH UOP's PROGRAM IN THE FIELD OF AUTOMOTIVE EXHAUST

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One important item which was touched on in UOP's testimony in connection with these EPA hearings(1) was that UOP's approach to this problem differs materially from that of some of the automobile companies. This relates to the relative role of catalysts and engine modifications in achieving the overall pollution abatement.

You have had testimony from several of the automobile companies in which they expressed as their underlying philosophy the reliance on automobile engine parameter modifications for eliminating the major part of the pollutants. They employ catalyst only as the final clean-up step. We believe that this is a natural point of view for automobile companies which are deeply grounded in the area of automotive design and have a natural distrust with regard to the potential of catalysts, an area of expertise which is foreign to their normal business.

UOP, however, strongly believes that this philosophy is not optimum. As experts in the field of catalysis with long experience in this area, we are much more confident as to the ability and the reliability inherent in catalysis. As such, we feel that the optimum approach to solving these problems lies in designing an engine to do its best possible job with regard to performance and economy and using a catalyst to do the principal part of the specialized job of exhaust gas clean-up. Thus, we recommend that the catalyst be required to work much harder than in the systems which some of the automobile companies are favoring.

(1) HEARINGS OF MARCH 15/1973

Aside from the much smaller penalties that this kind of an approach would incur with regard to performance and economy, a harder working catalyst system has, in our opinion, the very important advantage that it tends to operate with a higher catalyst temperature. The higher catalyst temperature, in turn, results in a much lower susceptibility to catalyst poisons since the reactions of most poisons with catalysts are reversible and the equilibrium degree of poisoning experienced with any particular exhaust gas poison concentration is less at higher operating temperatures. The use of a hard working catalyst system does, of course, require that the catalyst be thermally stable at these higher operating temperatures, but technology for making such a high stability catalyst is available and has been demonstrated by us.

The attached information which was obtained with one of UOP's base metal catalysts clearly illustrates this point. During the first 7,180 miles, the catalyst was run under conditions during which it had very little work to do and was therefore relatively cold. During this period substantial deactivation, particularly of carbon monoxide conversion, was experienced and the vehicle emissions rose above the 1975 standards. During the remainder of the 21,800 miles, the catalyst was subjected to various conditions which required more conversion performance and subjected it to periodic higher operating temperatures. The last period, between 14,800 and 21,800 miles, was carried out deliberately richening the engine by choking so that the amount of material to be burned by the catalyst was increased and the operating bed temperature held in the range of 1200 to 1400°F.

The emissions at the end of this period were .2 grams/mile for hydrocarbon and 2.64 grams/mile for carbon monoxide. This clearly shows that the catalyst is more stable when it is called upon to do more conversion.

The penalties, in terms of engine performance and fuel economy, when using a system in which the catalyst is not required to perform most of the pollutant removal, are particularly great for systems which will be required to meet the 1976 standards. UOP has long favored a system in which the single catalyst bed is used with an engine operated nearly at its optimum conditions and has so advised the automobile companies. The exhaust gases produced from such an engine, if carefully controlled, will be of such composition that the hydrocarbons, carbon monoxide and nitrogen oxides are simultaneously catalytically destroyed.

Operating an engine under these conditions calls for a much more precise control of the ratio of air to fuel than is obtainable in present-day engines or engines with the proposed modifications of carburetion or fuel injection. However, UOP believes that it is possible to develop a new system which, by a trimming mechanism for either carbureted or fuel injection engines, will provide a continuous automatic readjustment of the air-fuel ratio on the basis of the sensed composition of the exhaust gases using closed loop control.

Up to the present, we have not been able to interest any of the automobile companies nor, for that matter, EPA in carrying forward the kind of an aggressive development program on this type of self-tuning engine control system which we believe the urgency to provide this type of solution to the problem justifies. However, UOP's belief in the ultimate rightness of this type of approach is so strong that it is continuing to pursue the development of such a system solely with its own limited resources. Progress is being made and the program continues to show every promise of ultimate success. In the event that we are successful in this area, we intend to offer it generally to the automobile companies. We are, of course, making every effort to keep them informed as the work progresses.

**Automotive Products** Division
2454 Dempster Street
Des Plaines, Illinois 60016
Telephone 312-391-2000

August 21, 1973

Mr. Donald Hurter
Project Engineer
Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusettes 02140

Dear Mr. Hurter:

Thank you for your and Mr. Stuart's visit of August 16th. Had I known ahead of time your area of interest, I would have been better prepared and arranged more time for our conversation.

We have had some preliminary management discussions concerning UOP's participation in the DOT/EPA program and our interest remains high.

Enclosed are copies of UOP's 1972 Annual Report and several brochures describing UOP's history and general capabilities. Also enclosed is some descriptive material on UOP's three-component emission control system using a single catalyst bed and feedback control of air-fuel mixture. The Bureau of Mines data illustrates the HC, CO, and $NO_x$ control possibilities that can be achieved using a UOP three-component catalyst bed. We have concentrated most of our efforts in the carburetor feedback control system because this is the weakest technological link of the three-component control system. Assembling all of the elements for a three-component control system in a working road vehicle has been given a lower priority because the disclosure by Robert Bosch GmbH in SAE paper 730566 beautifully demonstrates the feasibility of the concept. We believe our designs for the sensing device and control system have substantial durability and producibility advantages over the comparative parts of the Robert Bosch system.

UOP's approach to achieving the goals you outlined would be to apply continuous feedback control to the air-fuel mixture and spark timing. Controlling the air-fuel mixture at stiochiometry during all modes of vehicle operation makes possible the use of single catalyst bed for the control of CO, HC, and $NO_x$. In addition, feedback control of air-fuel mixture and spark timing can result in large efficiency benefits. Even more important, the feedback control principal maintains the engine at peak efficiency and performance during all driving conditions, at all altitudes, in all weather conditions, for fuel composition variables, and through all stages of engine wear and deterioration throughout the life of the vehicle. This latter characteristic represents an important fuel conservation benefit over the vehicle that is manually tuned at periods determined by the owner's tolerance for poor performance; then at best, all carburetion and timing settings are a compromise for the many operating variables ahead.

uop
Universal Oil Products Company

As we discussed, the final measure of fuel economy is the total number of gallons of fuel a vehicle uses during its life divided by the total miles the vehicle traveled. Spot checks of fuel economy on a relatively new vehicle under arbitrary conditions of test for which the vehicle has been pre-adjusted are probably a poor measure of the real life fuel economy. We would like to suggest that rules be developed for this contest that recognize some method for the measurement of fuel economy that represents the total fuel used over an extended period of time. The time period should be long enough to cover engine deterioration, variations in vehicle use and maintenance, and other economy determining factors that vary with individual vehicle use.

We will appreciate your assistance in being introduced to the proper office in the Department of Transportation to receive instructions for submitting a contract proposal.

I would be pleased if UOP could be of additional assistance to your effort. Again my thanks for the infomation and guidance you have given us.

Sincerely,

Charles Bailey

Charles H. Bailey
Manager, Technical Services

United States Department of the Interior
BUREAU OF MINES
BARTLESVILLE ENERGY RESEARCH CENTER
P. O. BOX 1398
BARTLESVILLE, OKLAHOMA 74003

June 22, 1973

Memorandum

To: J. S. Ball, Research Director, BERC

From: R. D. Fleming, Project Leader, FCR, BERC.

Subject: Request for permission to release test data

This is a request for permission to release test data to Universal Oil Products (UOP) Company. The test data were obtained in the Bureau's program "Fuels and Engine Systems to Enhance Fuel Economy in Clean Air Cars."

The equipment used was a 1973 Chevrolet 350-CID engine modified to 10.25:1 compression ratio and was equipped with a single-bed catalytic converter (sometimes referred to as three-component control catalyst) for control of carbon monoxide, hydrocarbons, and oxides of nitrogen. The catalytic converter used on the engine was furnished by UOP.

The results of our tests using the UOP three-component control catalyst are tabulated in table 1. The performance of the catalytic converter system is shown in figure 1.

It is my understanding that UOP will submit these data to EPA at the Suspension Hearing in which certain automobile companies are applying for a delay in the enforcement of the 1976 Federal Emission Standards.

The data should be sent to:

Mr. Charles H. Bailey
Manager of Technical Services
Parzaust Retrofit Systems
Universal Oil Products Co.
Ten UOP Plaza
Des Plaines, Illinois 60016

Attachments

cc: Hurn

TABLE 1. - Emissions data on the performance of a single-bed three component control catalyst system (1973 Chevrolet 350-CID engine with 10.25:1 compression ratio operated at 60 mph cruise)

| Air-fuel ratio 1/ | Carbon monoxide |  | Hydrocarbon |  | Oxides of nitrogen |  | Exhaust gas temperature at converter inlet, °F | Catalyst bed temperature, °F |
|---|---|---|---|---|---|---|---|---|
|  | Concentration at converter outlet, pct | Conversion efficiency, pct 2/ | Concentration at converter outlet, ppmC | Conversion efficiency, pct 2/ | Concentration at converter outlet, ppm | Conversion efficiency pct 2/ |  |  |
| 14.19 | 0.98 | 56.2 | 590 | 68.3 | 190 | 91.3 | 1,110 | 1,330 |
| 14.38 | .58 | 69.4 | 350 | 80.4 | 163 | 92.8 | 1,110 | 1,360 |
| 14.46 | .41 | 78.2 | 250 | 85.8 | 150 | 93.4 | 1,110 | 1,360 |
| 14.51 | .31 | 84.0 | 186 | 89.5 | 170 | 92.4 | 1,120 | 1,370 |
| 14.54 | .26 | 85.7 | 198 | 88.7 | 165 | 92.9 | 1,110 | 1,360 |
| 14.58 | .18 | 89.8 | 135 | 92.0 | 200 | 91.3 | 1,120 | 1,370 |
| 14.64 | .08 | 95.2 | 93 | 94.5 | 390 | 83.8 | 1,120 | 1,370 |
| 14.68 | .04 | 97.6 | 69 | 95.9 | 600 | 75.0 | 1,130 | 1,360 |
| 14.69 | .05 | 97.0 | 75 | 95.8 | 450 | 78.8 | 1,120 | 1,380 |
| 14.72 | .03 | 98.1 | 75 | 95.6 | 675 | 71.9 | 1,120 | 1,360 |
| 14.73 | .04 | 97.5 | 66 | 96.2 | 550 | 74.1 | 1,120 | 1,370 |
| 14.79 | .03 | 98.1 | 65 | 96.1 | 1,180 | 51.0 | 1,120 | 1,350 |
| 15.06 | .02 | 98.6 | 83 | 95.0 | 1,620 | 26.1 | 1,120 | 1,340 |
| 15.07 | .02 | 98.5 | 71 | 95.6 | 1,580 | 29.2 | 1,120 | 1,340 |
| 15.20 | .02 | 98.5 | 75 | 95.5 | 1,820 | 14.4 | 1,120 | 1,320 |

1/ Air-fuel ratio determined from exhaust gas composition.

2/ Conversion efficiency = $\frac{\text{Concentration at converter inlet - concentration at converter outlet}}{\text{Concentration at converter inlet}}$ X 100.

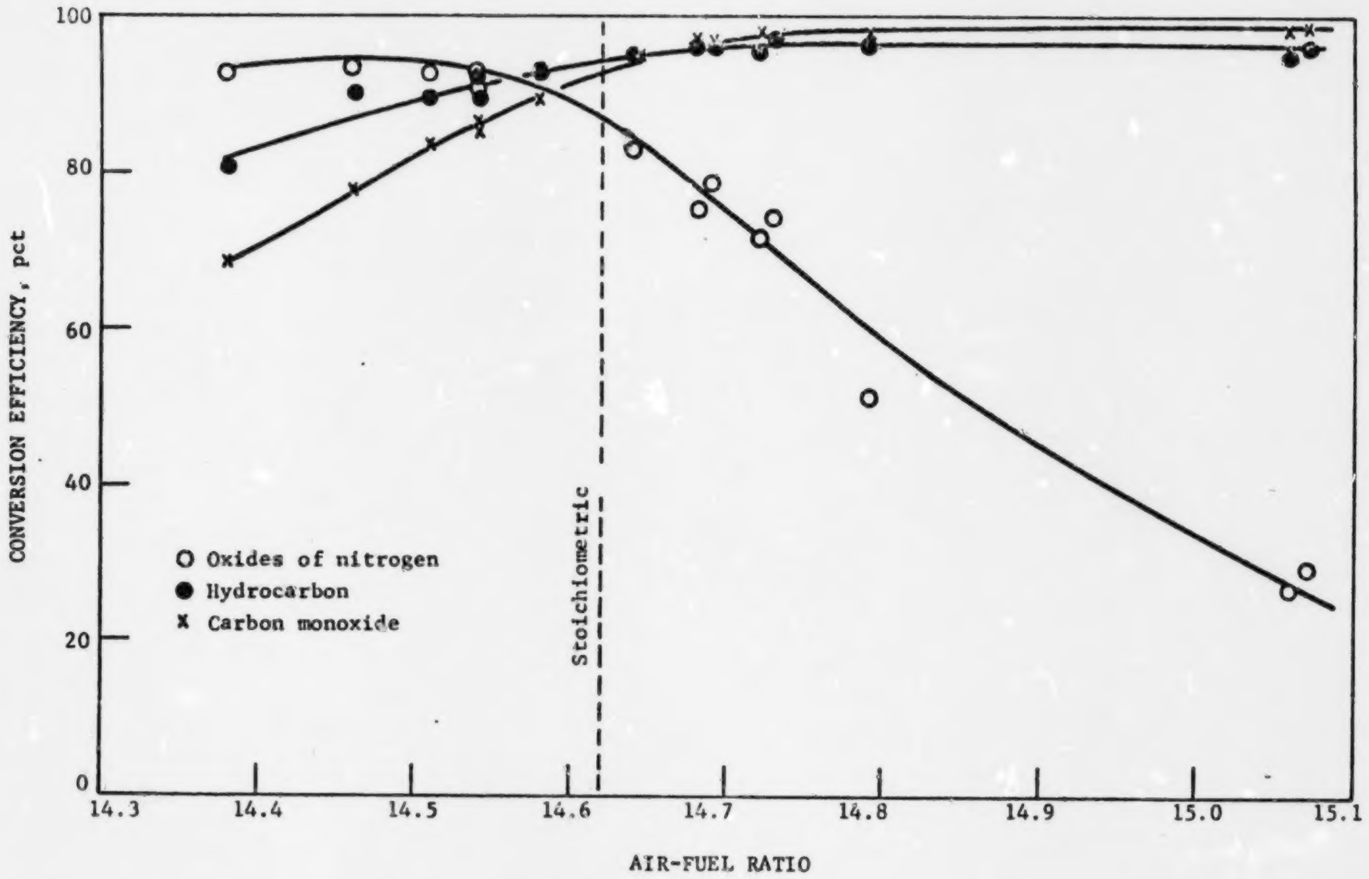


FIGURE 1. - Performance of a Single-Bed Three Component Control Catalyst System (1973 Chevrolet 350-CID Engine with 10.25:1 Compression Ratio Operated at 60 mph Cruise)

DEC 10 1973

GARRETT
AIRESEARCH INDUSTRIAL DIVISION
A DIVISION OF THE GARRETT CORPORATION
9225 AVIATION BLVD. • LOS ANGELES, CALIFORNIA 90009 • AREA CODE 213 • 670-7111

December 7, 1973

Mr. Donald Hurter
Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts 02140

Dear Mr. Hurter:

Enclosed is performance data taken from a 350 CID engine with 6:1 compression ratio. During all tests, the engine configuration was as follows: Water pump, A.I.R. pump and alternator (unloaded) were functioning; air conditioning and power steering pumps and the cooling fan were not used. All low- and mid-range torque values were taken at an air/fuel ratio of 15.5:1, while maximum power points were at 12.5:1. All data points are at spark settings of either mean best torque or borderline knock, whichever occurred first. Texaco unleaded fuel (91 octane) was used for all testing. Please note that on the computer output sheets "smoke reading" is actually spark timing in degrees BTDC.

I feel this information should be helpful to you in evaluating the benefits of turbocharging for increased fuel economy and power increases.

If there are any questions regarding the enclosed data, please feel free to write or call me at any time.

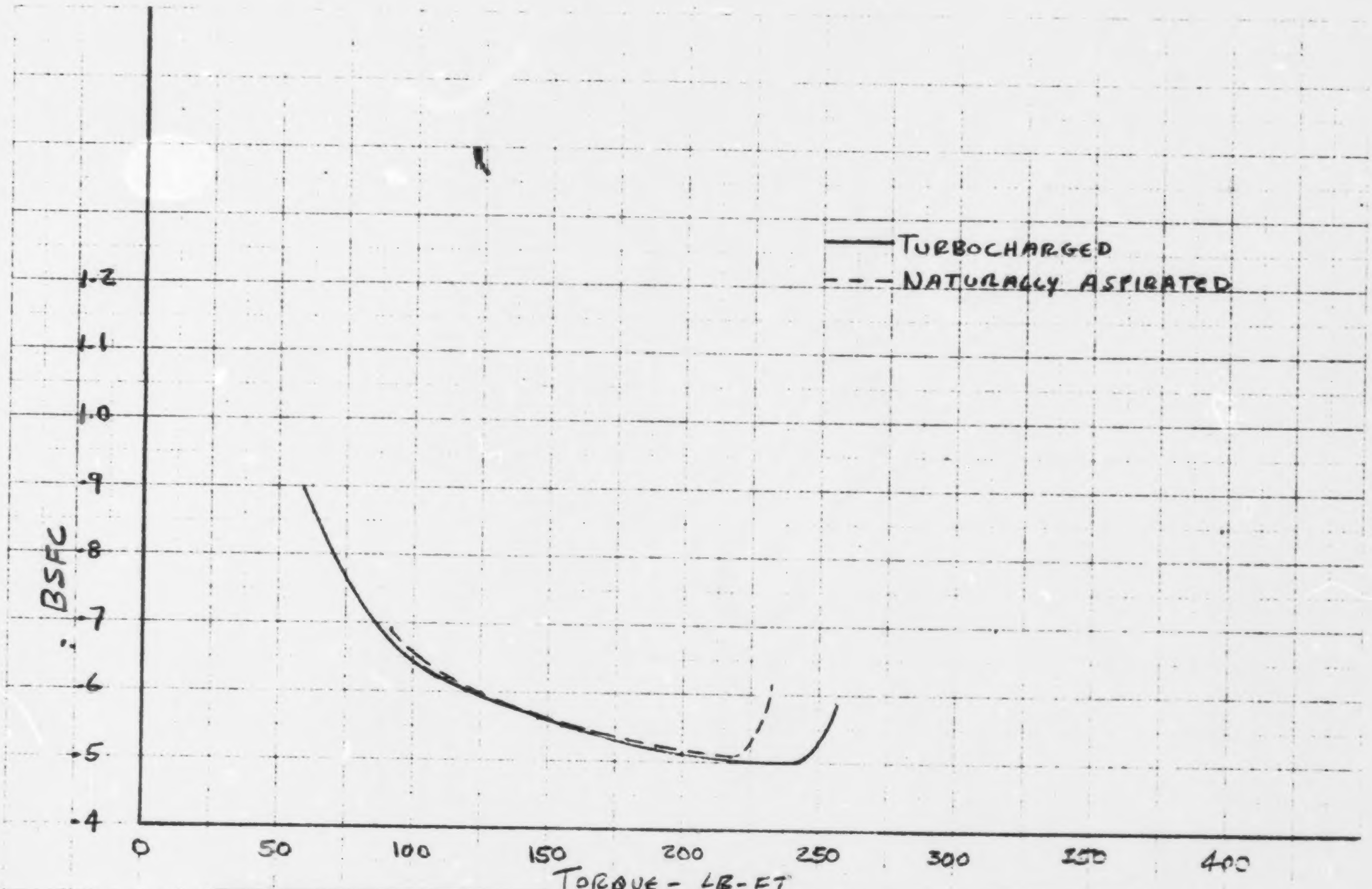
Very truly yours,

AIRESEARCH INDUSTRIAL DIVISION

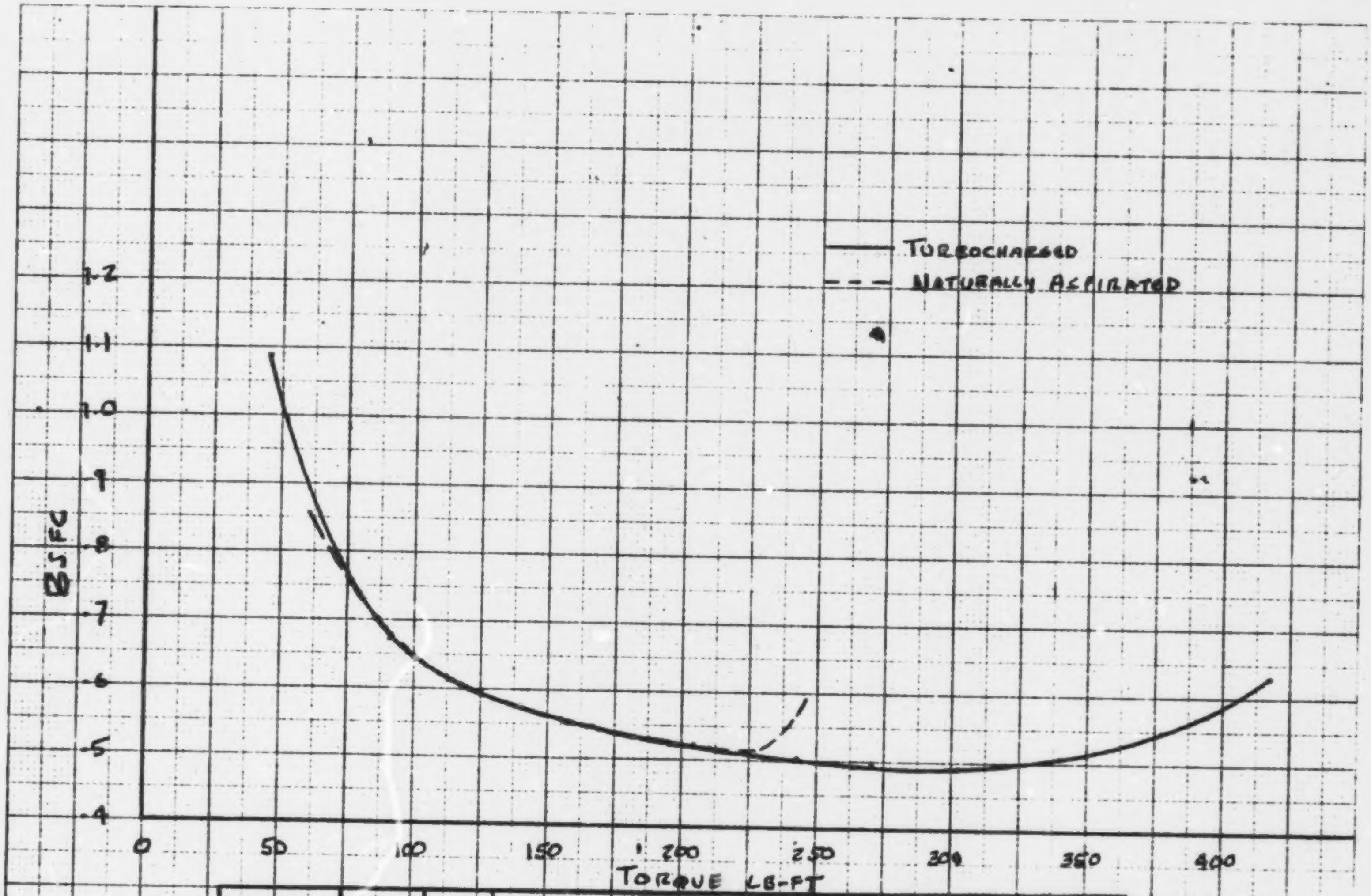
C. E. McInerney
C. E. McInerney

CEM/mfs

Encl.

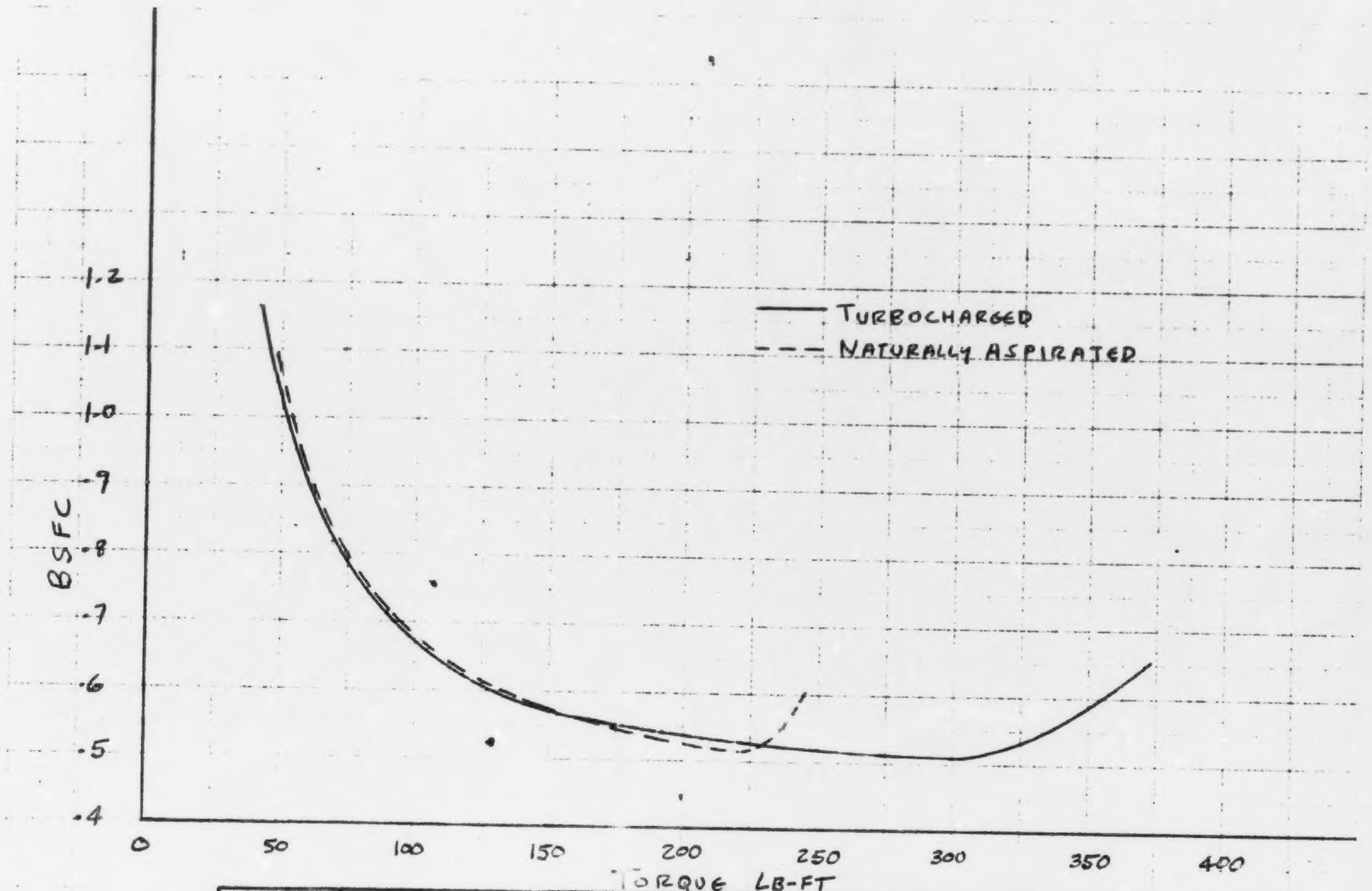


| | | | | |
|---|---|---|---|---|
| CALCULATED BY | | | 350 CUBIC INCH 6:1 C.R<br>1500 RPM | 72.27C |
| TRACED BY | 12-6-73 | JJ | | |
| CHECKED BY | | | | |
| APPROVED BY | | | AIRESEARCH INDUSTRIAL DIVISION<br>LOS ANGELES CALIFORNIA | |

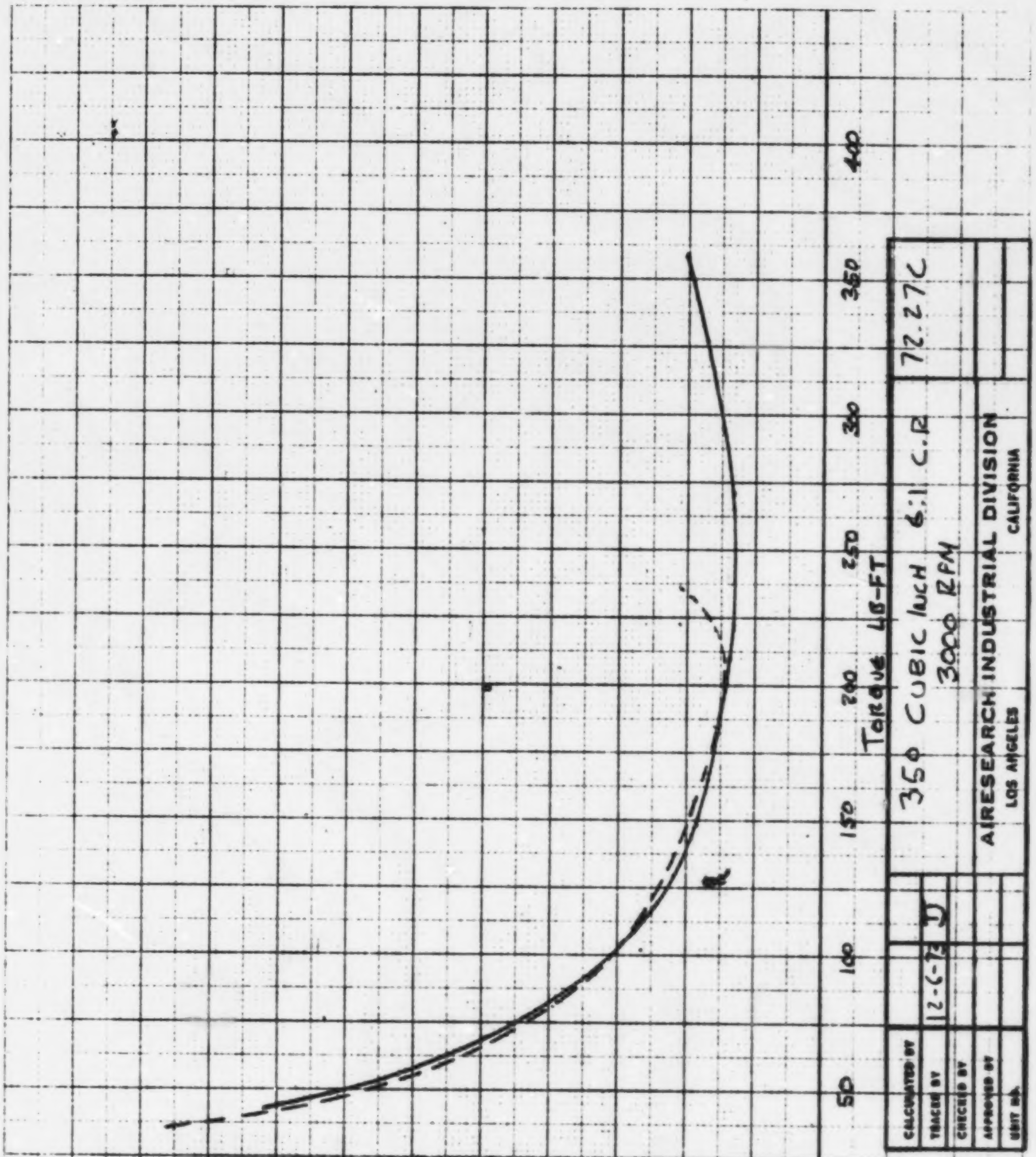


| | | | | |
|---|---|---|---|---|
| CALCULATED BY | | | 350 CUBIC INCH 6:1 C.R<br>2000 RPM | 72.27 C |
| TRACED BY | 12-7-73 | TJ | | |
| CHECKED BY | | | AIRESEARCH INDUSTRIAL DIVISION<br>LOS ANGELES CALIFORNIA | |
| APPROVED BY | | | | |
| UNIT NO. | | | | |

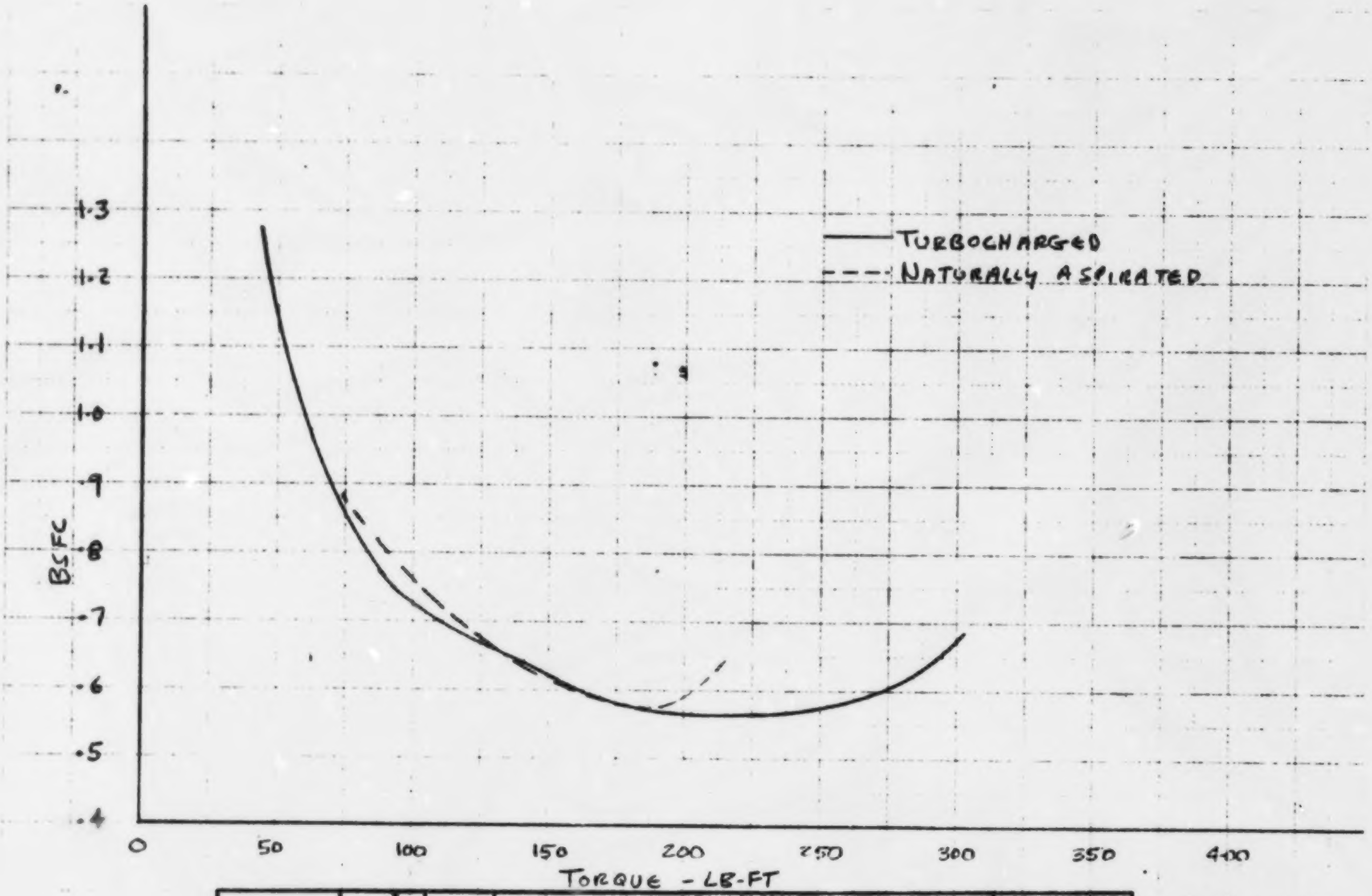
AID FORM 4193-3



| | | | | |
|---|---|---|---|---|
| CALCULATED BY | | | 350 CUBIC INCH 6:1 C.R<br>2500 RPM | 72.27C |
| TRACED BY | 12-7-73 | D | | |
| CHECKED BY | | | | |
| APPROVED BY | | | AIRESEARCH INDUSTRIAL DIVISION<br>LOS ANGELES CALIFORNIA | |
| UNIT NO. | | | | |



AID FORM 4193-3



| | | | | |
|---|---|---|---|---|
| CALCULATED BY | | | 350 CUBIC INCH 6:1 C.R<br>3500 RPM | 72.27.C |
| TRACED BY | 12-6-73 | JJ | | |
| CHECKED BY | | | | |
| APPROVED BY | | | AIRESEARCH INDUSTRIAL DIVISION<br>LOS ANGELES CALIFORNIA | |
| UNIT NO. | | | | |

## CONTACT REPORT: AIRESEARCH, LOS ANGELES, JAN. 10, 1974

Met with Charles McInerney of Airesearch to review its test program on its automotive turbocharger and to see what data it would make available to substantiate its claim of improved fuel economy by using a smaller displacement engine turbocharged to replace the present naturally aspirated Chevrolet 350 cu. in. V-8 in a Chevelle, maintaining constant performance.

We went over the data on the 350 in.$^3$ engine run at 6:1 compression ratio, both turbocharged and naturally aspirated, which he had sent to David Lee of Arthur D. Little, Inc. These data show the output that Airesearch obtained at this compression ratio with optimum spark advance. He indicated that they were able to go to 15 lb/in.$^2$ manifold pressure at 2000 rpm using a 91 octane fuel, giving a torque of 417 lb-ft or a B.M.E.P. of 150 lb/in.$^2$ He did not have good data on the standard engine with a 8.5:1 C.R. for comparison and these tests are going to be run in the near future.

I question the ability to operate satisfactorily at that manifold pressure with a 91 research octane number commercial gasoline with a motor method octane number of 81.

The compression ratio of the standard 350 cu.$^3$ engine is about 8.5:1 for satisfactory operation on a 91 octane fuel. Under these conditions the engine develops a B.M.E.P. of about 120 lb/in.$^2$ Lowering the compression ratio to 6:1 will reduce the octane requirement to about 75 O.N. with a B.M.E.P. of about 105. Raising the B.M.E.P. at the 6:1 C.R. back to 150 should result in an octane requirement of well over 100 O.N., as it is the B.M.E.P. that really limits the engine output on a given O.N. fuel. The normal practice is to lower the compression ratio and then bring the B.M.E.P. at 2000 rpm back to nearly the same level of 120 lb/in.$^2$ and take advantage of the higher power from the turbocharged engine at higher speeds. I know of no magical way of raising the B.M.E.P. to the levels that Airesearch claims it can, without increasing the octane requirement.

One also has to remember it is the expansion ratio that controls the thermal efficiency of the I.C. engine. It is the combined factors of lower thermal efficiency and loss in torque that make it difficult for the turbocharged engine to compete on a basis of economy, as the axle ratio has to be increased to give the same low-speed performance before the turbocharger becomes effective.

I recommended that he make an overall comparison, starting with the base engine of 350 in.$^3$ and 8.5:1 C.R. as a baseline and then run a 265 or 283 V-8 turbocharged engine at 6:1 C.R. at the best output that he could obtain with 91 octane fuel. In that way he would have data to prove his claim that it would give better B.S.F.C. than the base engine at the same output torque. He felt it should be done on a 6-cylinder engine, which might be more feasible, as it probably could be made to go under the hood, which the present one will not do as its design utilizes a drawn carburetor rather than a pressure carburetor.

McInerney did not submit any data on octane requirement vs. mainfold pressure on his tests of the Chevrolet 350 in.$^3$ engine, but did show me the results of other tests comparing naturally aspirated and turbocharged output on the 350 in.$^3$ Chevrolet. The performance changes in these tests showed more normal increases in output than the tests submitted to A.D. Little, Inc.

# DIESEL PERFORMANCE MAPS

Prepared by

Ricardo Consulting Engineers

RICARDO CONSULTING ENGINEERS

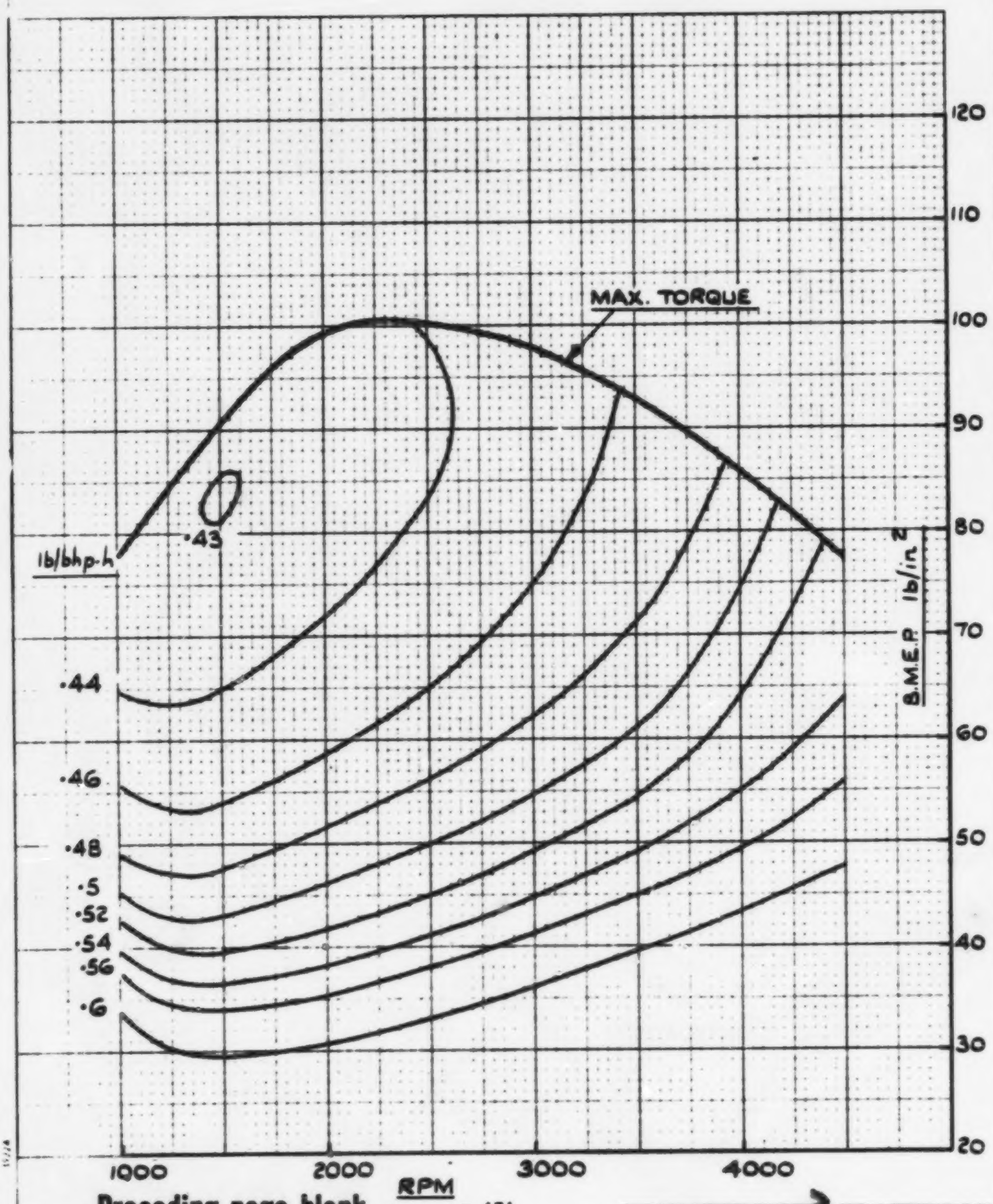
FIG. No.
Drg. No D24426
Date 10·10·73

# PERFORMANCE MAP OF

I

## 90 × 83 mm 129 cu. in.

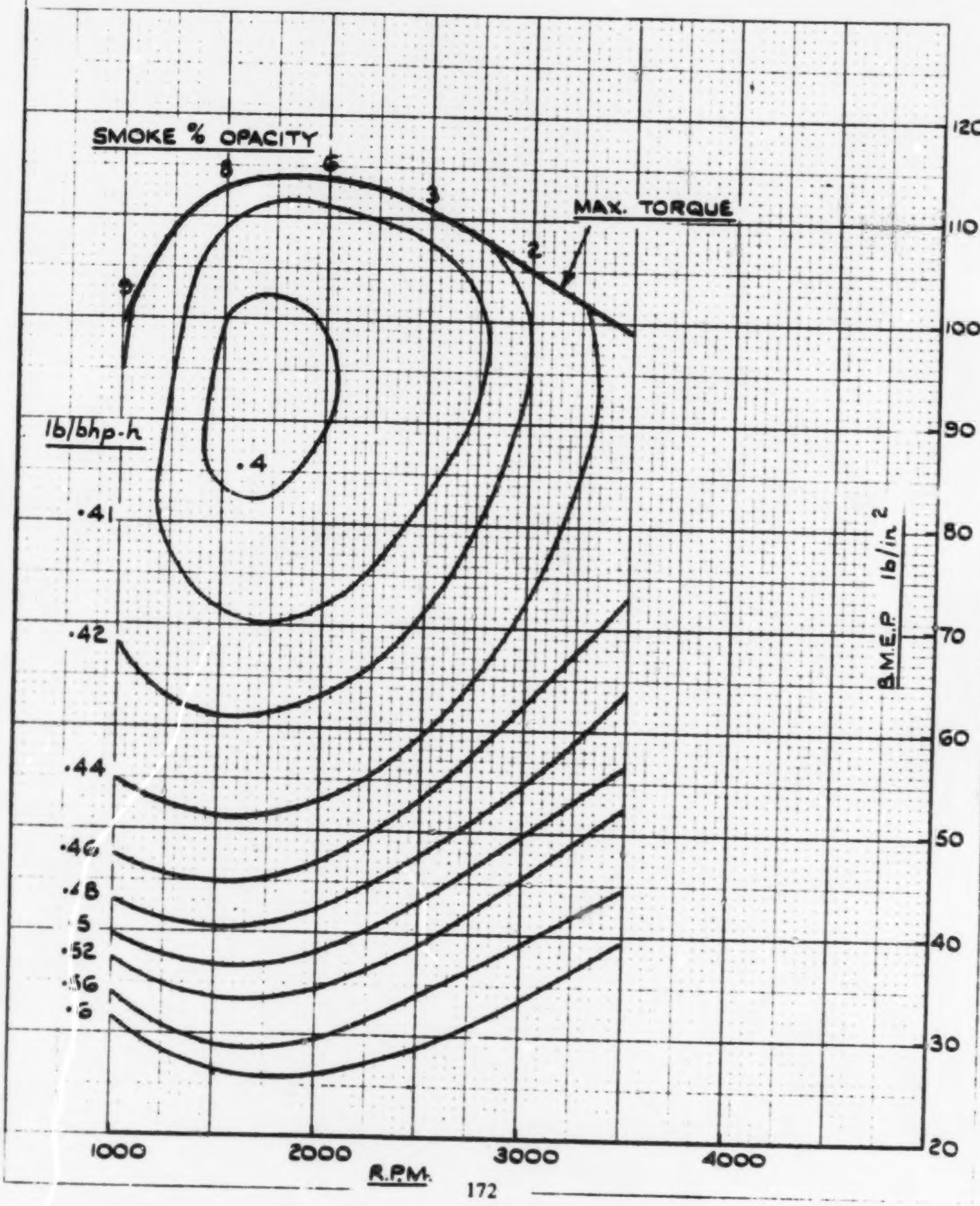
## RICARDO COMET V COMBUSTION SYSTEM.



**RICARDO CONSULTING ENGINEERS**

FIG No.
Drg. No. D24427
Date 10-10-73

## PERFORMANCE MAP OF
## A = 3·5 x 4·0 in. 153 cu. in.
## RICARDO COMET V COMBUSTION SYSTEM.



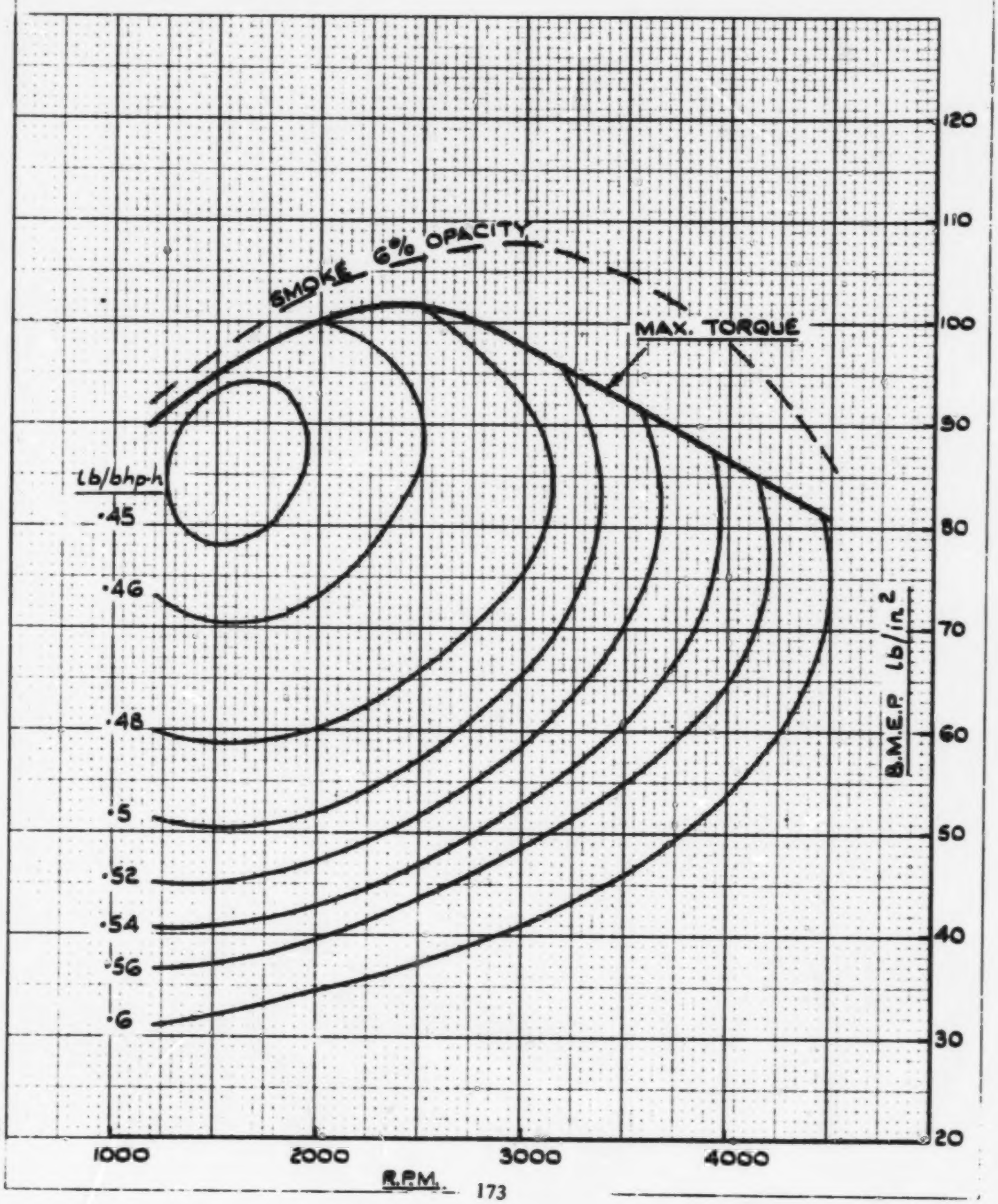
RICARDO CONSULTING ENGINEERS

FIG. No.
Drg. No. D24428
Date 10-10-73

## PERFORMANCE MAP OF

Y = . 88 × 85mm. 126 cu. in.

## RICARDO COMET V COMBUSTION SYSTEM.



RICARDO CONSULTING ENGINEERS

FIG. No

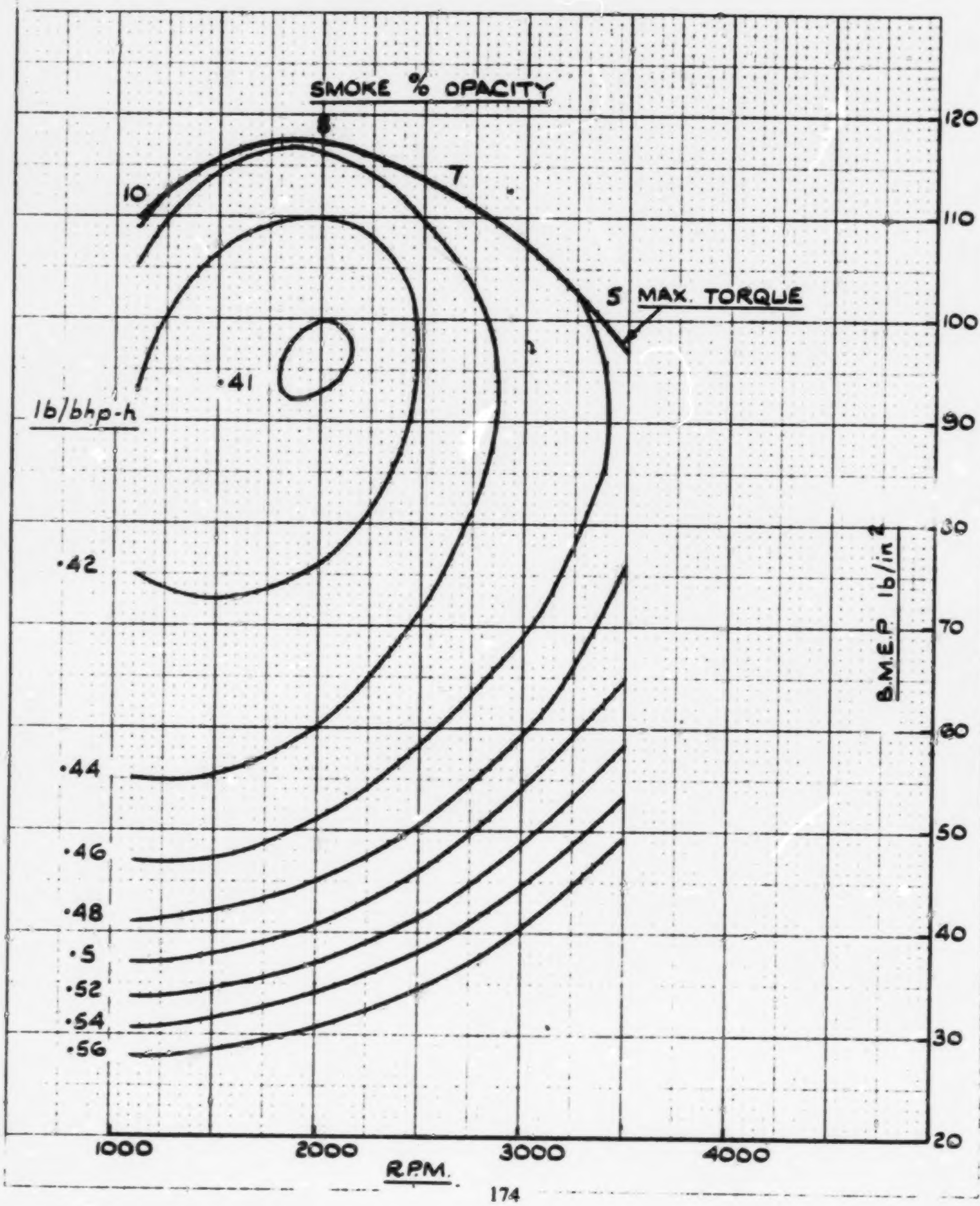
Drg. No 024429

Date 10-10-73

## PERFORMANCE MAP OF

## H = 95 x 100mm, 171 cu. in.

## RICARDO COMET V COMBUSTION SYSTEM.



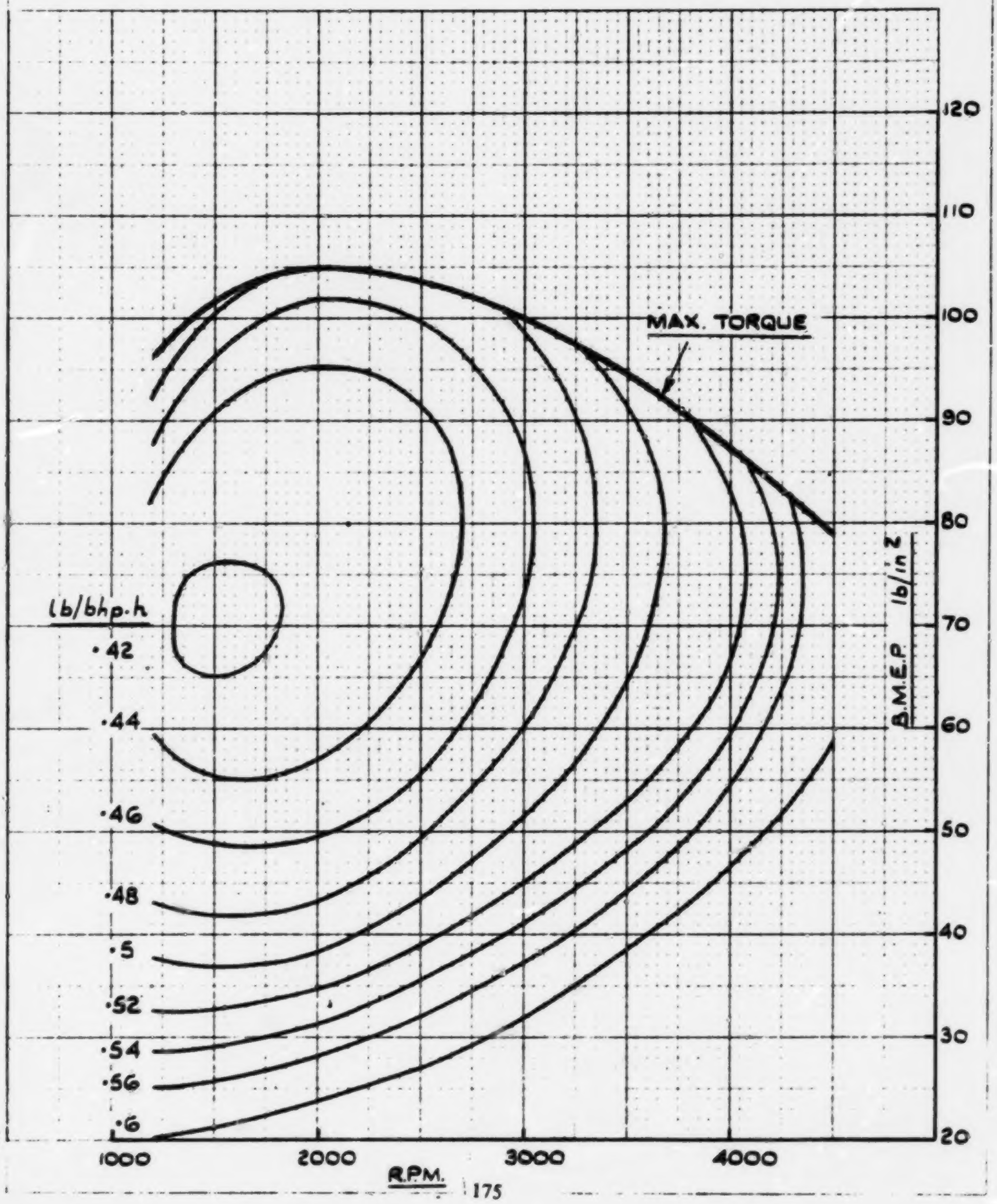
RICARDO CONSULTING ENGINEERS

FIG. No.
Drg. No. D24430
Date 10·10·73

## PERFORMANCE MAP OF

## D = 87 × 83·6 mm. 122 cu. in.

## MERCEDES PRECHAMBER COMBUSTION SYSTEM.



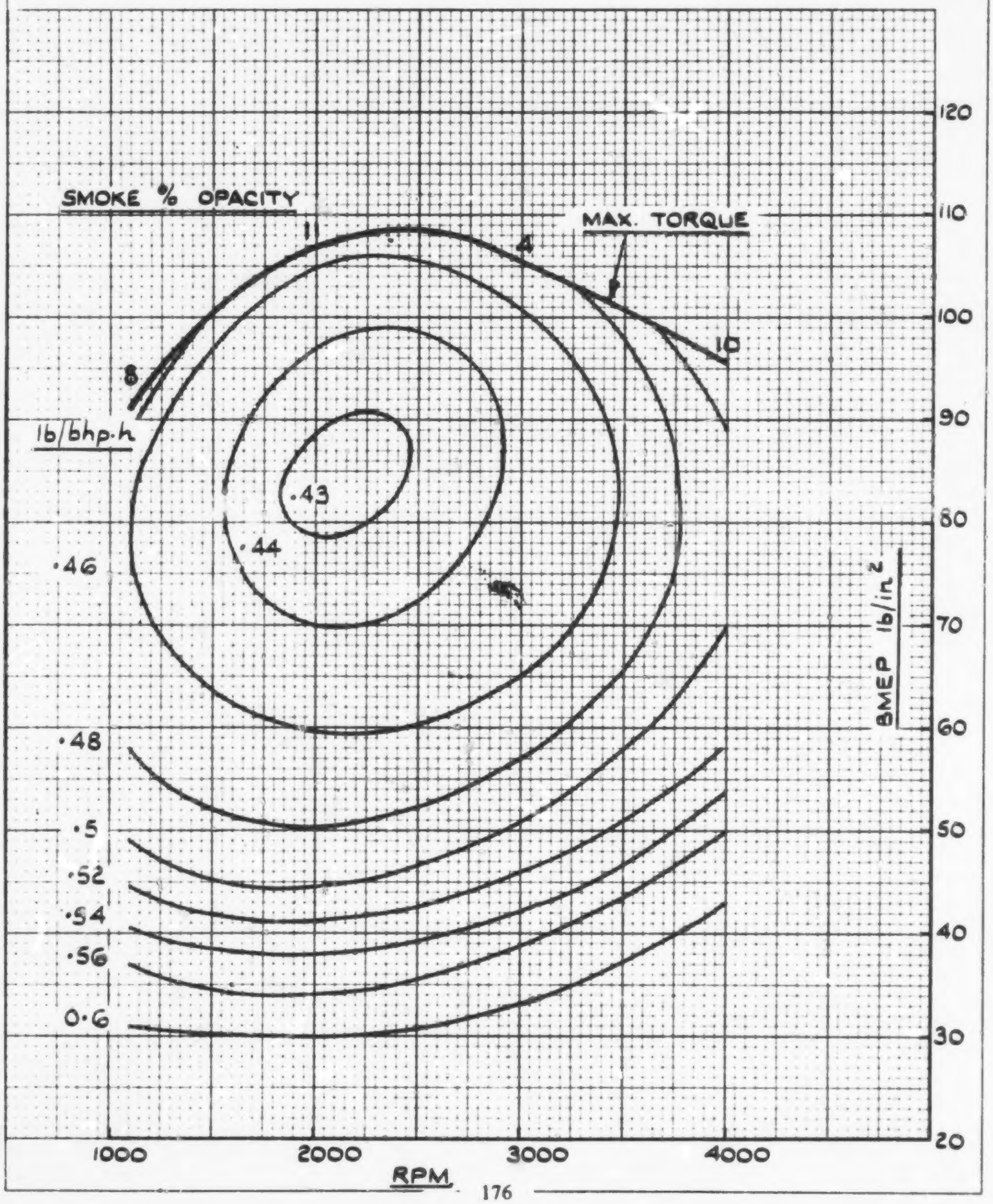
RICARDO CONSULTING ENGINEERS

FIG. No.
Drg. No. D24494
Date 19-10-73

PERFORMANCE MAP OF

X = 3·688 × 3·229 in. 138 cu. in.

RICARDO COMET V COMBUSTION SYSTEM.



# APPENDIX III-2

# TRANSMISSION PERFORMANCE CURVES

# SCHEMATICS AND CHARACTERISTICS OF TRANSMISSION PERFORMANCE CURVES

Prepared by

BORG-WARNER CORPORATION

November 6, 1973

Characteristic output torque and power curves of various transmission types

Comparison plots - A-1

Two speed transmission with torque converter
Ratios 1.82, 1.00
Schematic A-2

Two speed transmission with torque converter
Ratios 1.72, 1.00
Schematic A-3

Two speed transmission with torque converter and lockup clutch
Ratios 1.54, 1.00
Schematic A-4

Three speed transmission with torque converter
Ratios 2.40, 1.47, 1.00
Schematic A-5

Three speed transmission with torque converter and lockup clutch
Ratios 2.30, 1.43, 1.00
Schematic A-6

Three speed, non-shifting, torque converter transmission
Ratios 2.67, 1.67, 1.00
Schematic A-7

Four speed manual gear box transmission
Ratios 3.94, 2.40, 1.43, 1:00

Four speed transmission with fluid coupling
Ratios 3.82, 2.63, 1.45, 1.00

Hydrostatic transmission, positive displacement pump and motor
Ratio range 4.0:1.

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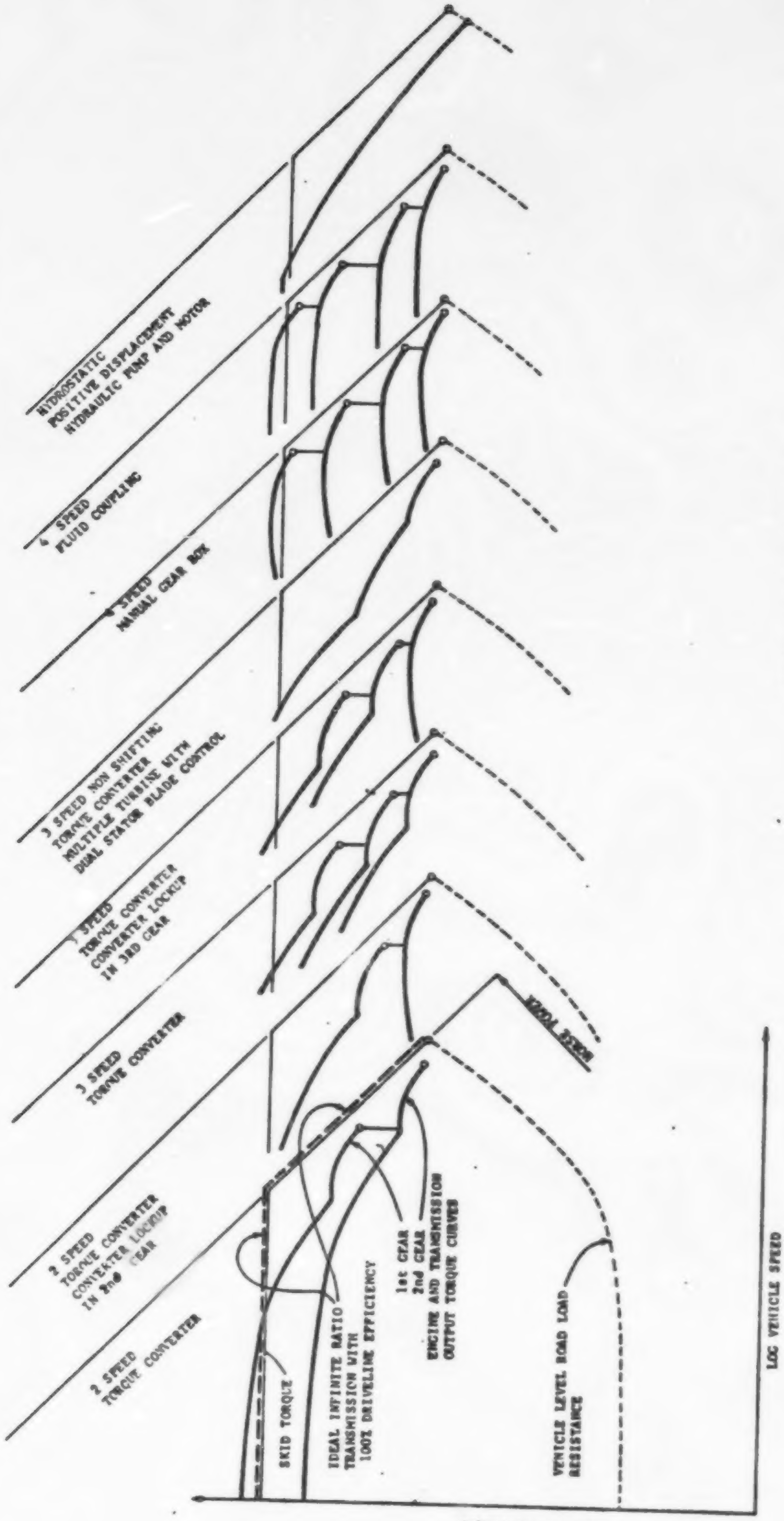
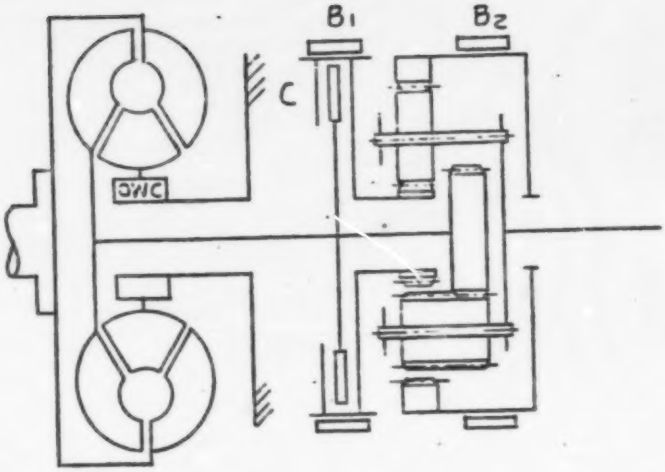


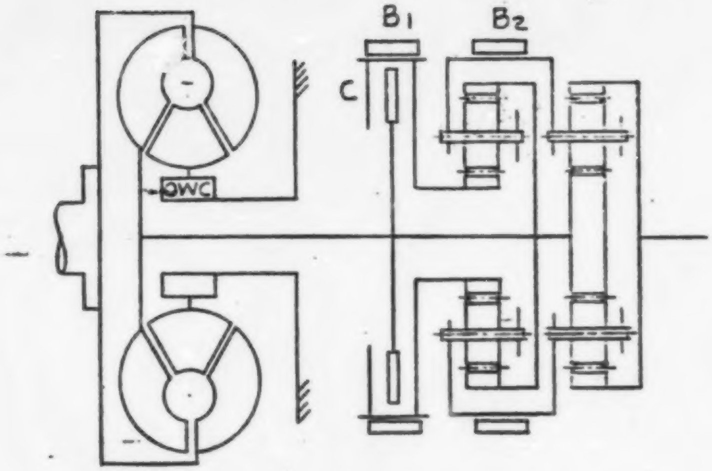
CHARACTERISTIC OUTPUT TORQUE AND POWER CURVES OF VARIOUS TRANSMISSION TYPES

## TWO SPEED TRANSMISSION WITH TORQUE CONVERTER



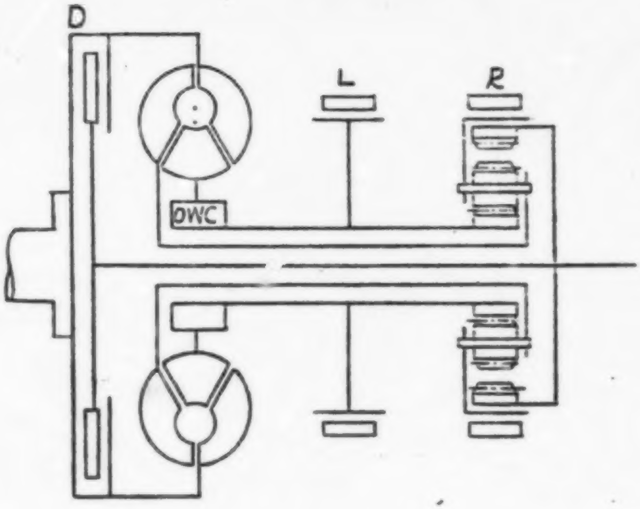
| | C | B1 | B2 | RATIO |
|---|---|---|---|---|
| REVERSE | | | ON | 1.82 |
| FIRST | | ON | | 1.82 |
| SECOND | ON | | | 1.00 |

## TWO SPEED TRANSMISSION WITH TORQUE CONVERTER



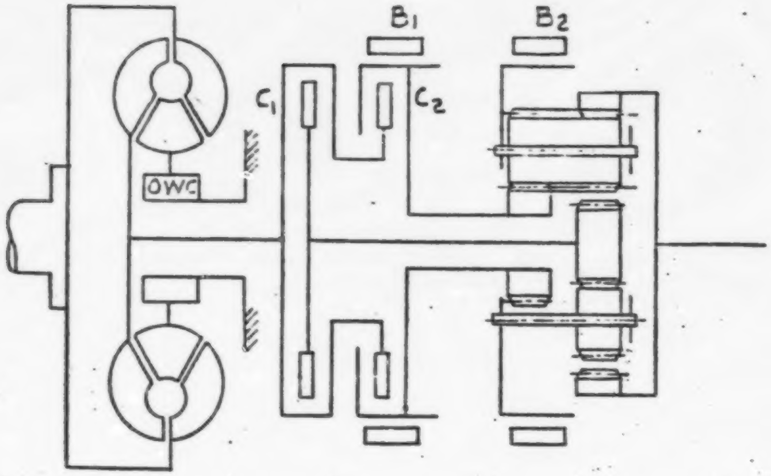
| | C | B1 | B2 | RATIO |
|---|---|---|---|---|
| REVERSE | | | ON | 2.39 |
| FIRST* | | ON | | 1.72 |
| SECOND | ON | | | 1.00 |

## TWO SPEED TRANSMISSION WITH TORQUE CONVERTER AND LOCKUP CLUTCH



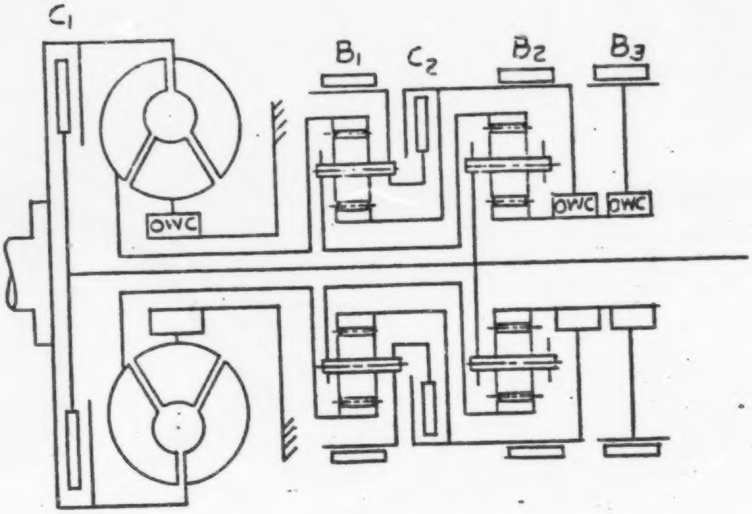
| | | D | L | R | RATIO |
|---|---|---|---|---|---|
| REVERSE | | | | ON | 2.85 |
| NEUTRAL | | | | | |
| DRIVE | LOW | | ON | | 1.54 |
| | DIRECT | ON | | | 1.00 |
| LOW | | | ON | | 1.54 |
| HILL RETARDER | | ON | | ON | |

## THREE SPEED TRANSMISSION WITH TORQUE CONVERTER



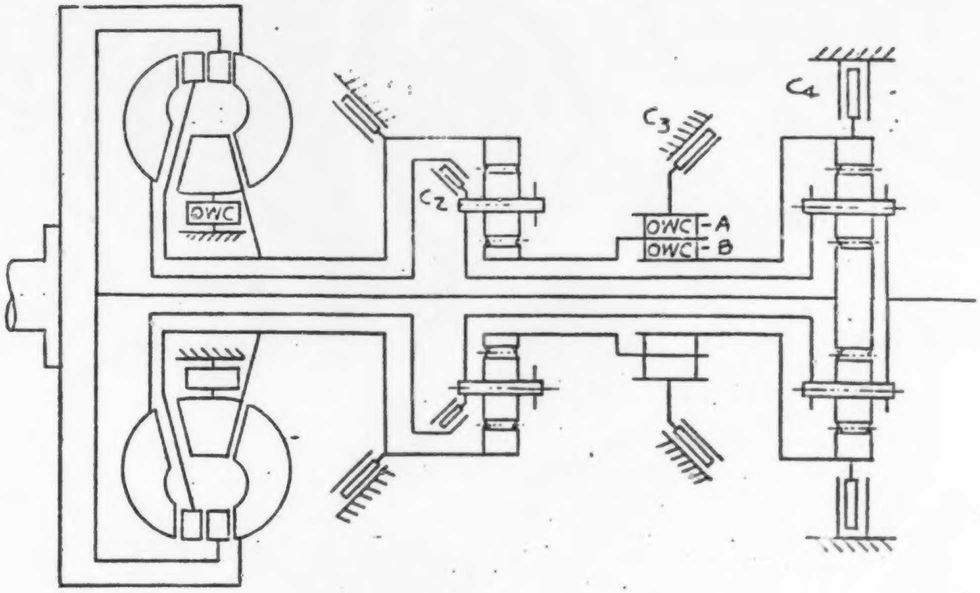
| | C1 | C2 | B1 | B2 | RATIO |
|---|---|---|---|---|---|
| NEUTRAL | | | | | |
| FIRST | ON | | | ON | 2.40 |
| SECOND | ON | | ON | | 1.47 |
| THIRD | ON | ON | | | 1.00 |
| REVERSE | | ON | | ON | 2.00 |

THREE SPEED TRANSMISSION WITH TORQUE CONVERTER AND LOCKUP CLUTCH


C1
B1
C2
B2
B3
OWC
OWC
OWC

| | $C_1$ | $C_2$ | $B_1$ | $B_2$ | $B_3$ | RATIO |
|---|---|---|---|---|---|---|
| REVERSE | | | ON | | | 2.009 |
| FIRST | | | | ON | ON | 2.309 |
| SECOND | | ON | | | ON | 1.435 |
| THIRD | ON | | | | ON | 1.000 |

THREE SPEED, NON SHIFTING,
TORQUE CONVERTER TRANSMISSION
(MULTIPLE TURBINE WITH DUAL STATOR BLADE CONTROL).



| | C1 | C2 | C3 | C4 | OWC-A | OWC-B | GEAR RATIO |
|---|---|---|---|---|---|---|---|
| PARK | | | | | ON | | |
| REVERSE | ON | ON | | | ON | ON | 1.78 |
| NEUTRAL | | | | | ON | | |
| DRIVE | | ON | ON | | ON/OFF | ON/OFF | 2.67<br>1.63<br>1.00 |
| GRADE RETARD | | | | ON | ON | | 2.67 |

## SUMMARY REPORT OF MEETING AT ORSHANSKY TRANSMISSION CORP.

The Orshansky Corporation is designing a multirange hydromechanical truck transmission which will be financed and built by Mack Truck, and developed and tested by both organizations. It should be ready late in 1974. Orshansky is also designing and building on its own a multirange automotive transmission which should be available for test in mid-1975. The basic problems with the automotive design are found in: (1) maintaining high efficiency over a wide range of torque/speed variation, (2) reducing the hydraulic noise; and (3) developing stable and reliable control systems that will enable the engine and transmission to operate under optimum conditions, regardless of the road load or speed of the vehicle.

The Orshansky-designed truck transmission that is being financed and built experimentally by the Mack Truck Co. and since it is their most advanced design, we reviewed it first, following through the various shift modes. Mr. Orshansky stated that two of the critical problems with the multirange transmissions of the hydromechanical type were the controls and the noise from the hydraulic units. To minimize the problems in developing a transmission, they are using commercially available units wherever possible. At present, the hydraulic units are being furnished by Eaton, which is working on the noise problem, and the Orshansky consultant is also going to attack the problem in the Orshansky laboratory.

Olsen went through the control system which, on the Mack truck, will use all spool valves to control the hydraulic circuits. The automotive version will have electronic controls, which will greatly simplify the control system. The parts for the

Mack truck transmission are being fabricated by Mack with a spare transmission and parts to be furnished to Orshansky for test and development. They are hoping to have these by late this year.

There are only two operating transmissions now available; one is located in a race car to which is being added a regular V-8 engine, so that it might be of some value. The other is located in a large John Deere tractor, their present demonstrator. It makes a poor demonstrator, however, because the engine noise is so great one cannot hear much else. However, we did ride the tractor and the shifts proved to be smooth with the movement of a single lever enabling the driver to go from low to high range and into reverse with the engine running at constant speed.

Whether they can get the hydraulic noise down to a satisfactory level for passenger car use appears to be the biggest development problem. The Mack truck transmission should give a preview of this problem.

Another important development problem is to get optimum efficiency in automotive service. This means putting as little through the hydraulic system as possible and having the majority of the operation through the efficient gear train.

The Orshansky Corporation will build this automotive transmission on its own so that the potential of this type of transmission in improving fuel economy can be demonstrated.

More detailed information on the Orshansky transmission can be found in S.A.E. Paper 72074, "Characteristics of Multiple Range Hydromechanical Transmissions" by Eli Orshansky and William E. Weselah.

**ORSHANSKY TRANSMISSION CORPORATION**

PETER HUNTLEY, *Vice-President*
18 Bellevue Road
Belmont • Massachusetts 02178
(617) 489-2419

December 27, 1973

Mr. Donald Hurter
Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts 02140

Dear Don,

I appreciate David's comments made on Friday regarding the necessary sensitivity of the throttle control in the region where best fuel economy at various engine speeds occurs at almost constant throttle settings. Although I have not considered this to be a serious problem with the 302 cubic inch V-8 which has been studied in detail, I believe that in the general case he is absolutely correct.

The solution, which of course is applicable with any type of continuously variable transmission, is as shown in the sketch. By making the desired engine speed a direct function of pedal position (instead of a function of throttle plate angle), full control over the driveline is attained however flat the optimum throttle .v. rpm curve happens to be. Given the signal representing desired engine speed and the signal from the crankshaft governor giving actual engine speed, the error in engine speed is used in the usual manner to correct the transmission gear ratio.

There is a bewildering variety of control philosophies which have been implemented in drive trains with continuously variable transmissions. In this connection, the following patents assigned to General Electric should be referenced:

| | | |
|---|---|---|
| 3,292,449 | issued | 12/20/66 |
| 3,324,740 | " | 6/13/67 |
| 3,368,425 | " | 2/13/68 |
| 3,489,036 | " | 1/13/70 |

Yours sincerely,

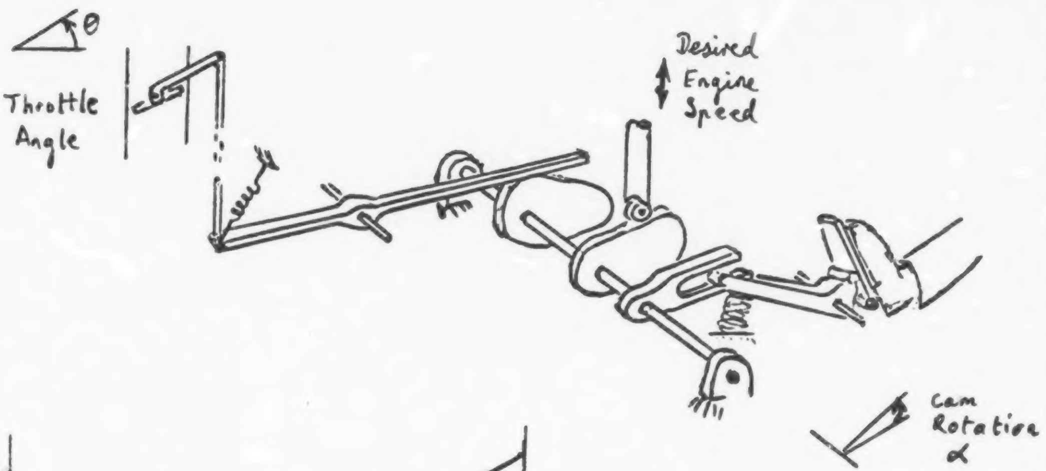
Peter Huntley
Vice President

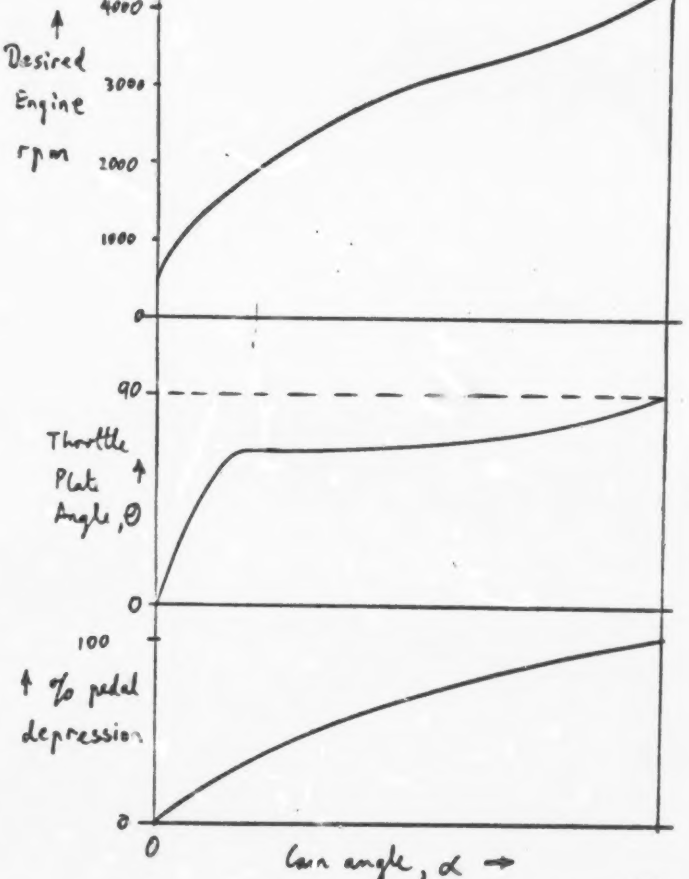
PH/jmw

Enclosure-Sketch

# Generation of Desired Engine Operating Schedule

Dec 1973


θ
Throttle Angle
Desired Engine Speed
Cam Rotation α



# APPENDIX III-3

# OIL ADDITIVES

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**CLIMAX MOLYBDENUM COMPANY OF MICHIGAN**
1600 HURON PARKWAY · ANN ARBOR, MICHIGAN
TELEPHONE 313 761-2300
RESEARCH LABORATORY
P.O. BOX 1568 48106

January 10, 1974

Mr. Donald A. Hurter
A. D. Little, Inc.
Engineering Division
Cambridge, Mass.

Dear Mr. Hurter:

Dave Gresty and I would like to thank you for the opportunity to review the technical merits of the use of $MoS_2$ in motor oils. We believe the product has unusual applicability in reducing the fuel consumption of internal combustion engines. The use of $MoS_2$ motor oils would appear to be particularly apropos in view of the energy crisis.

In the attachment, we have attempted to answer the eleven questions posed during our discussion concerning the percent fuel improvement expected and the possible deleterious effects of the product on engine performance. We have data to substantiate the statements made. In addition to the reports Dave sent to you prior to the meeting, we have enclosed copies of the Ethyl Corp. reports on engine performance when using $MoS_2$ motor oils.

If we can be of any further service, please let us know.

Very truly yours,

H. F. Barry

H. F. Barry
Manager, Chemical Research

HFB:cac

cc: D. A. Gresty

A SUBSIDIARY OF
AMAX
AMERICAN METAL CLIMAX, INC.

## The Use of $MoS_2$ Motor Oils for Improved Fuel Economy

(1) What evidence is there for an improvement in fuel consumption due to the use of $MoS_2$ motor oils; what is the average percent improvement?

The reduction in fuel consumption due to the use of $MoS_2$ in motor oils has been documented in tests conducted by the Ethyl Corporation, Automotive Research Associates, and Loughborough Consultants Limited. These data are summarized in reports RP-29-69-02, RS-222 and RS-230. The tests covered engine dyanometer and vehicle track tests. In addition, the improvements in fuel consumption due to $MoS_2$, has been confirmed in Climax school bus tests and in employer leased company car fleet tests. Overall, the average percent reduction in fuel consumption is about 5%. Individual values have varied from 2% to a 12% improvement.

(2) What is the source of the improved fuel economy?

The major source of the improved fuel economy is the reduction in engine friction [mainly (it is believed) in the ring-belt area]. The reduction in friction has been confirmed in engine motoring tests conducted at the Ethyl Corporation Laboratories. In the motored (unloaded) engine friction tests, the reduction in friction is more pronounced in the high rpm range. It is believed, the degree of improvement in friction will be noted as well at the lower rpm, if in fact the BMEP is raised to provide high power output at low engine speed.

(3) Are there deleterious effects due to $MoS_2$ operation?

The possible negative effects of $MoS_2$ on engine operation have been examined. The tests have included engine operating conditions designed especially to examine: (a) pre-ignition, (b) octane-requirement increase, (c) sludge and varnish, (d) wear, (e) oil-consumption and (f) emissions.

In 100 hour Oldsmobile tests, the data to-date, have indicated that there is no deleterious effect on pre-ignition or ORI. There is some evidence, in fact, that the use of $MoS_2$ will reduce the tendency of engines "to rumble".

API-MS - VB (engine sequence) tests have indicated consistent reductions in sludge and varnish when $MoS_2$ is added to the oil. The $MoS_2$ effect on engine wear has been generally slightly favorable. In modern engines, wear is essentially negligible during the first 50,000 miles; it is therefore hard to statistically attribute small changes in wear to the beneficial effects of $MoS_2$ but the trend is positive.

(3) Continued

Because of the $MoS_2$ suspension system used, the effects of the $MoS_2$ additive on oil consumption have been generally favorable. In most tests, oil economy has either been improved or else there has been no change.

The effect of the small amount of sulfur leaving the combustion chamber that is derived from the $MoS_2$ motor oil has been calculated and compared to the sulfur derived from the gasoline. In the attached table, it is indicated that the $MoS_2$ contributes about 1.5% of the sulfur that is emitted in the exhaust stream.

In the Federal Hot-Start emission cycle tests, the effect of $MoS_2$ motor oils on exhaust emissions of hydrocarbons, CO and $NO_X$ was determined. The cars were examined in 4000 mile increments from 0 to 20,000 miles. In essence, there was no effect of $MoS_2$ on auto exhaust emissions either favorably or unfavorably.

(4) What are the marketing problems for the use of $MoS_2$ motor oils?

The major problems that have been experienced in the past that have restricted the marketing effort for $MoS_2$ are:

(a) The product is black

(b) $MoS_2$ is insoluble in oils

(c) $MoS_2$ costs more than ordinary organic chemical additives

(d) Some segregation of blending, storage and shipping facilities would be required

(e) The use of $MoS_2$ motor oils has suffered because of over-zeoulous promoters who made exaggerated claims and incorporated miniscule amounts of $MoS_2$ in their products.

(5) Will the average motorist save money by using $MoS_2$?

We have calculated the economics of the savings possible through the use of the $MoS_2$ additive:

Basis: 1 year

Mileage driven = 12,000 miles

Fuel consumption = 12 mpg

Oil change interval = 6,000 miles

Cost of fuel = 50¢/gal.

Cost of $MoS_2$ additive = \$1.00/oil change

(5) Continued

Cost of Gasoline:

$$\text{Base case} = \frac{12,000}{12} = 1,000 \text{ gal.} \times \$.50 = \$500/\text{year}$$

$MoS_2$ case = 0.95 ($500) = $475

Gross Savings = $500--475 = $25/year

Cost of additive = $1 x twice per year = $2

Note: The additive is added only at the time of the oil change.

∴ Net savings = $25--2 = $23.00/year for fuel.

(6) What is the raw material supply situation?

The amount of $MoS_2$ required for a 100 million car population is:

100 million x 0.1 lb/yr/car = 10 million lbs/yr of $MoS_2$ required

Currently, the free-world produces about 300 million lbs/yr. of $MoS_2$, and the production is expected to increase by an additional 100 million lb/yr. during the period 1977-80. While most of this material is not designed to go to lubricant usage,market demand will dictate its final disposition.

(7) How long would it be before the $MoS_2$ motor oil system could be adopted?

The $MoS_2$ additive concept is something that is available now. The product has been exhaustively tested and proven in over a million miles of track tests, over-the road passenger cars and school busses.

(8) What about the use of other solid lubricants?

The use of other solid lubricant additives such as graphite and Teflon have been considered in the past by various investigators.

It has been found that most natural graphites are marginally abrasive; the synthetic graphites are expensive and they will not form an adherent film on a ferrous substrate.

Reportedly, powdered or small particle sized Teflon has been evaluated as a motor oil additive. The results, apparently were mixed and to our knowledge this material has not been developed for crank-case use.

(9) Should $MoS_2$ motor oils be included in the original manufacturing operation?

It is believed that the energy crunch can best be served by having the car manufacturer's and OEM accounts utilize $MoS_2$ during their assembly and break-in operations. This method of operation would also alert the ultimate user to replenish his oil with a $MoS_2$ containing product since it was used in the "factory-fill".

(10) Does $MoS_2$ contribute to easier engine starting and during the engine warm-up period?

It is expected that the use of $MoS_2$ will have a second-order beneficial affect on fuel consumption due to its beneficial effect on increased cranking speed at low temperatures. This reduction in friction should also prove to be beneficial during the entire "warm-up" period during which time fuel consumption is higher than the ultimate steady-state value when the engine is at operating temperature.

(11) What about the effects on other mechanical parts of the vehicle?

$MoS_2$ is widely used in chassis and front-wheel bearing greases. $MoS_2$ is also added to hypoid gear-oils by certain specialty lubricant manufacturers. Thus, $MoS_2$ can contribute, in another small way, to the mechanical efficiency of other moving parts of the vehicle.

## SULFUR EFFECTS

### Fuel

Assume 0.1% S in the fuel.

For 15,000 miles @ 15 mpg = 1000 gal. of gasoline are consumed

$$\text{lbs. of fuel} = 1000 \times \frac{6.5\ \text{lb}}{\text{gal}} = 6500\ \text{lbs.}$$

$$\text{lbs. of } \underline{S} \text{ emitted} = 6500 \times .001 = 6.5\ \text{lbs} =$$

$$\text{gms. of } \frac{S}{\text{mile}} = \frac{6.5 \times 454}{15{,}000} = \frac{0.197\ \text{gms.}}{\text{mile}}\ \underline{S}$$

### $MoS_2$

Assume 1% $MoS_2$ in the crankcase.

$$\text{Assume oil consumption} = \frac{1000\ \text{miles}}{\text{qt.}}$$

$$1.8\ \text{lbs. of } \frac{\text{oil}}{1000\ \text{miles}} \text{ are used} = \frac{818\ \text{gms.}}{1000\ \text{miles}}$$

$$1\%\ MoS_2 = \frac{8.18\ \text{gms. of } MoS_2}{1000\ \text{miles}} = \frac{3.28\ \text{gms.}}{1000\ \text{miles}}\ \underline{S}$$

$$= \frac{.0033\ \text{gms.}}{\text{mile}}\ \underline{S}$$

Recipients of this data shall in no way express or
imply in any advertising or publicity that these tests
were made by the Ethyl Corporation, or that the product
involved has the endorsement of the Ethyl Corporation

Project 90704-6

Report No. RS-222

# THE EFFECT OF MOLYBDENUM DISULFIDE IN THE CRANKCASE OIL ON ENGINE PERFORMANCE

Contract Evaluation for
The Climax Molybdenum Company of Michigan

Report By ______________ Date 2-13-63

Ethyl Corporation Research Laboratories
Ferndale, Michigan

# FOREWORD

This report covers tests conducted by the Ethyl Corporation to find the effect of adding molybdenum disulfide to the crankcase oil on engine performance and economy. This work was done for the Climax Molybdenum Company of Michigan under a contract agreement. Climax's interest in the possible benefits in this area were aroused by the claims of some commercial suppliers of upper cylinder lubricants and crankcase oil additives. Tests from a few testing laboratories supported these claims, and Climax's own field experience added enough credence to justify further investigation. The tests covered by this report were contracted in order to find whether or not there is a potential improvement in power and economy via $MoS_2$, and whether this improvement is large enough to justify further development work on $MoS_2$ as a crankcase lubricant additive.

Both Ethyl and Climax are well aware of the general skepticism with which technical people in the automotive and petroleum industries regard data showing increased power and economy due to crankcase oil additives. This skepticism is no doubt largely due to the spectacular claims often made by "Mouse Milk" marketers usually unsupported by test data; and perhaps to a lesser extent to a historical inability to find a practical oil additive which would substantially reduce engine friction. Every effort was made to conduct the tests so as not to prejudice the results in any way and to minimize the possibility of changes in engine conditions, weather, etc.

Tests were conducted with and without $MoS_2$ at a 1% wt concentration in two oils. One oil was a premium grade compounded oil containing a dispersant, and the second oil was a non-additive straight mineral oil.

The intent of this report is to describe the test equipment and procedures, document operating experiences, and to present results. No attempt will be made to interpret the results as we feel that this should be the prerogative of the sponsor.

The contract agreement specifies that Climax Molybdenum will in no way express or imply in any advertisement or publicity that this test was made by the Ethyl Corporation or that the product involved has our endorsement. However this agreement does not prohibit their use of our name as having been the contractor who conducted the tests in their technical presentations to customer companies.

## DISCUSSION OF RESULTS

Test results are shown in tabular form in Table 1, and graphically in Curve Sheets I and II. The reliability of the data and the possible effects of uncontrolled variables are commented on below. These comments are general in nature and are based on our past experience in engine work. Although every effort was made to control all known conditions which might effect engine performance, there remain some unknown and uncontrollable variables which adversely effect accuracy. Atmospheric conditions for instance constitute one variable which cannot be controlled and which is known to effect engine power. Correcting these data to standard atmospheric conditions largely but not completely compensates for this. Engines also change somewhat from day to day, and while this change may be very slight it can be significant when trying to detect small differences.

### Brake Power

The power data are corrected to a standard barometric pressure of 29.53 in. hg. of dry air. Carburetion changes between runs should not have changed the power output measurably as the variation in full throttle air-fuel ratio was no more than 0.2. I feel that our power data are within a 1% accuracy range.

### Friction

Motoring friction measurements are probably influenced more by the technique of the observer than by changes in the engine. In these tests with the same observer making all observations these readings should also be within a 1% accuracy range.

### Brake Specific Fuel Consumption

Specific fuel consumption is inherently less reproducible than power measurements since both the power and the fuel flow rate measurements are subject to about 1% inaccuracy. Changes in atmospheric moisture is one uncontrolled and uncompensated variable as water vapor in the air draws fuel through the carburetor but does not contribute to power. Fortunately for these runs the change in water vapor pressure was almost nil between comparable runs.

Specific fuel consumption at road load is unfortunately less accurate than at full throttle. At road load the observations are subject to the same inaccuracies as at full throttle in addition to which there is the difficulty of maintaining an accurate part throttle load setting.

Variations in carburetor flow characteristics can effect fuel economy significantly and for this reason we like to keep air-fuel ratios within a 0.2 range between comparable runs. The size of this effect largely depends upon which part of the fuel response curve the engine is operating on. Carburetors are usually designed to operate near best power air-fuel ratio at full throttle, and in the range of 12.0 to 12.5 to 1 there is very little effect on power from changing fuel flow rates. Consequently at full throttle the fuel economy or pounds of fuel per brake horsepower hour is quite sensitive to air-fuel ratio. At road loads carburetors are designed to operate nearer to their best economy setting where changes in fuel rate do effect power directly. Since both fuel flow and power change in the same direction the change in fuel economy is relatively small.

These data I regard as being within 2% at full load, and at road load I expect may vary from 5% at low speed to 3% at the high speed end.

## Crankcase Blowby

Crankcase blowby measurements are made by sealing the breather opening and connecting the road draft tube to a conventional gas meter of the type used for metering gas for residential use. The measuring equipment is accurate to 2% when properly maintained and blowby observations made in quick succession are generally reproducible within ± 0.1 cfm. The blowby itself however varies considerably from day to day due to piston ring rotation and a see-saw pattern of as much as 0.4 cfm is not unusual. Blowby measurements can be very useful as a rough indication of cylinder and ring condition, but day to day variations of less than 0.5 cfm are not regarded as significant.

## Compression Pressures

These measurements are highly useful as an indication of valve condition but as in crankcase blowby observations day to day variations are often quite high. Ethyl's criteria of valve failure is a 25 psi pressure loss at 200 rpm, but at that loss the valve condition is still not bad enough to be detected in power output or engine roughness.

The last set of compression pressure readings on the Oldsmobile engine were consistently lower than the preceeding checks. The consistency leads me to suspect a faulty gage check valve as valve failure is nearly always random in nature. Unfortunately this gage was not cross checked. The cylinder heads were subsequently removed however and visual valve inspection showed that the valve faces and seats were in good condition.

# TEST EQUIPMENT

## Engines

The engines used for this test were selected because of their availability in our laboratory. Rather than go to the expense of buying and running in new engines, we selected engines from our stock which were in good mechanical condition, reasonably representative of modern production, and which had already had enough service to eliminate the need for more break-in time. Both were standard production models. One engine; the Chevrolet, was a truck engine which we modified to the extent of installing a passenger car distributor and carburetor. The other engine, an Oldsmobile, was used without modification. For this test they were run without fan, generator, oil filter or air filter. The specifications of these engines as we used them are as follows:

| | | |
|---|---|---|
| Make and Model | 1960 Chev. Truck | 1961 Olds 88 |
| Cylinder Arrangement | V-8 | V-8 |
| Displacement, cu. in. | 283 | 394 |
| Bore and Stroke, in. | 3.875 x 3.000 | 4.00 x 3.69 |
| Compression Ratio | 8.0:1 | 8.75:1 |
| Carburetor Model | RP2GC, 7019052 | RP 2GC, 7013008 |
| Distributor Model | DR 1110947 | DR 1110968 |
| Previous Hours Service | 43 | 800 |

## Power Absorption and Measurement

A General Electric, direct-current dynamometer with a Ward-Leonard loading and control system was used as the power absorption unit. Torque measurements were made by means of a Toledo scale linked to the dynamometer. This linkage and scale was calibrated at the start and mid-point of the test and was found to be no more than 0.1 lb off at any point in our operating range, with no change in calibration between checks.

## Air Measurements

Air flow was measured by means of calibrated round-edge orifices in a surge tank.

## Fuel Flow

Fuel rates were measured volumetrically by timing the flow through burettes. These readings were corrected for fuel temperature.

## Engine Speed

Engine revolutions were counted by an American Standard Chromo-tach. During timed runs the speed was maintained by using a cathode-ray tachometer.

## Crankcase Blowby

A Sprague 175, 300 cfh capacity, gas meter was used to measure the blowby rate from the crankcase. This meter is connected only during actual observations in order to minimize the time to which it is exposed to the corrosive, oil bearing blowby gases. Exposure time is thus held to less than five minutes per run. These meters are cleaned and calibrated at [illegible]-hour intervals or less in order to preserve reasonable accuracy.

### Compression Pressures

Compression pressures are measured with an Ethyl Compression Pressure Gage developed especially for this purpose. This equipment consists of a [illegible]-lb. Bourdon tube gage with a check valve, and a manual pressure release valve.

## TEST FUEL

A premium quality laboratory fuel; Indolene, was used throughout the test. This fuel was used without TEL in order to minimize combustion chamber deposit accumulation during the test. Inspection data are as follows:

| | | |
|---|---|---|
| Fuel No. | 1193-62 | |
| Gravity, °API | 58.8 | |
| Vapor Press., psi | 7.4 | |
| Distillation | | |
| IBP | 99°F | |
| 10% Evaporated @ | 143°F | |
| 50% " " | 218°F | |
| 90% " " | 299°F | |
| FBP | 390°F | |
| Existent Gum, mg/100 ml | 2.6 | |
| Sulfur Content | 0.019% wt | |
| Octane Number | Motor | Research |
| @ 0 TEL | 86.8 | 97.1 |
| Hydrocarbon Type | | |
| Aromatics | 25.0% | |
| Olefins | 6.0% | |
| Saturates | 69.0% | |

## CRANKCASE LUBRICANT

This test included runs on both a straight mineral oil and a premium grade compounded oil containing a dispersant. This was done to find whether a dispersant was necessary to keep the $MoS_2$ in suspension to effect friction. Since there was very little background experience on how well or how long the $MoS_2$ would stay suspended in either oil, we took the added precaution of stirring the oils containing this compound until it was put in the engine. Whenever the engine was shut down for more than 30 minutes the oil was drained and stirred until we were ready to start.

Inspection data on the two base oils is as follows:

| | | |
|---|---|---|
| Brand | Encofleet | Havoline |
| Refiner | Humble Oil Co. | The Texas Co. |
| Designation | SAE 20 | SAE 20 |
| Test Oil Number | 2050-62 | 2058-62 |
| Gravity, °API @ 60°F | 28.5 | 28.2 |
| Viscosity, Saybolt Sec. @ 100°F | 304 | 354 |
| " " @ 210°F | 51.9 | 57.5 |
| Viscosity Index | 91.0 | 109.0 |
| Ash, % | 0.0043 | 0.945 |
| Sulfur, % | 0.122 | 0.40 |
| Total Acid Number, mg KOH/g | 0.0 | 1.4 |
| Total Base Number, mg KOH/g | 0.0 | 2.4 |
| Metals Present, % (Spectrographic) | | |
| Ca | Trace | Trace |
| P | None | 0.104 |
| Zn | None | 0.073 |
| Ba | None | 0.53 |

Table 1

## DATA SUMMARY

## EFFECT OF $MoS_2$ ON ENGINE PERFORMANCE

| Engine | Oldsmobile | | | Chevrolet 283 | |
|---|---|---|---|---|---|
| Crankcase Oil | Havoline HD | | | Encofleet | |
| $MoS_2$ in Oil | None | 1% wt | | None | 1% wt |
| Hrs. on Oil | 4 | 4 | 20 | 24 | 21 |
| **Brake Power (1)** | | | | | |
| 800 rpm | 41.8 | 42.6 | 41.7 | 30.4 | 30.6 |
| 1200 " | 70.3 | 71.4 | 71.1 | 48.6 | 49.5 |
| 1600 " | 97.9 | 98.7 | 98.7 | 66.4 | 67.3 |
| 2000 " | 125.1 | 125.6 | 126.6 | 83.8 | 84.0 |
| 2400 " | 152.3 | 151.9 | 154.6 | 100.7 | 100.2 |
| 2800 " | 170.1 | 172.5 | 173.8 | 114.1 | 112.4 |
| 3200 " | 180.8 | 183.4 | 184.7 | 120.2 | 122.0 |
| 3600 " | 187.6 | 190.9 | 194.6 | 125.7 | 126.8 |
| 4000 " | 191.7 | 195.4 | 197.5 | 127.1 | 129.6 |
| **Friction Horsepower (2)** | | | | | |
| 800 rpm | 4.6 | 4.6 | 4.4 | 3.0 | 3.0 |
| 1200 " | 7.5 | 7.5 | 7.3 | 4.5 | 4.5 |
| 1600 " | 11.2 | 11.2 | 11.0 | 7.1 | 6.9 |
| 2000 " | 16.8 | 16.3 | 16.0 | 10.4 | 10.0 |
| 2400 " | 24.1 | 23.3 | 22.3 | 14.2 | 14.0 |
| 2800 " | 33.0 | 31.5 | 30.0 | 18.6 | 18.7 |
| 3200 " | 42.3 | 40.6 | 39.1 | 24.0 | 23.8 |
| 3600 " | 54.1 | 51.9 | 50.0 | 30.4 | 29.9 |
| **Brake Specific Fuel Cons. (@ A/F)** | | | | | |
| LB/BHP/HR | | | | | |
| **Full load** | | | | | |
| 800 rpm | .659 (10.5) | .653 (10.6) | .667 (10.6) | .580 (11.7) | .570 (11.8) |
| 1200 " | .554 (11.7) | .560 (11.6) | .561 (11.5) | .563 (12.1) | .544 (12.0) |
| 1600 " | .525 (12.1) | .526 (11.9) | .527 (11.8) | .536 (12.7) | .527 (12.3) |
| 2000 " | .510 (12.1) | .507 (12.2) | .511 (11.9) | .515 (13.0) | .516 (13.1) |
| 2400 " | .494 (12.4) | .491 (12.5) | .496 (12.2) | .511 (12.8) | .521 (12.9) |
| 2800 " | .514 (12.4) | .507 (12.4) | .504 (12.4) | .514 (12.6) | .533 (12.7) |
| 3200 " | .534 (12.4) | .524 (12.4) | .526 (12.4) | .548 (12.5) | .535 (12.7) |
| 3600 " | .553 (12.5) | .543 (12.5) | .539 (12.4) | .565 (12.5) | .551 (12.6) |
| 4000 " | .576 (12.5) | .564 (12.6) | .565 (12.5) | .592 (12.5) | .572 (12.7) |
| **Road load** | | | | | |
| 1200 rpm | 1.31 (12.8) | 1.32 (13.4) | 1.31 (12.5) | 1.16 (11.3) | 1.15 (11.4) |
| 1600 " | 1.15 (13.5) | 1.14 (13.4) | 1.10 (13.2) | 1.02 (12.8) | 0.77 (13.2) |
| 2000 " | .929 (14.2) | .921 (13.9) | .917 (14.1) | .841 (13.6) | .837 (13.8) |
| 2400 " | .851 (14.3) | .840 (14.3) | .838 (14.4) | .757 (13.7) | .738 (13.9) |
| 2800 " | .781 (15.6) | .758 (14.8) | .760 (14.5) | .684 (14.0) | .651 (14.7) |
| 3200 " | .724 (15.1) | .712 (15.2) | .702 (14.8) | .649 (14.3) | .634 (14.9) |
| 3600 " | .697 (15.3) | .679 (15.5) | .677 (15.0) | .610 (14.6) | .601 (14.9) |
| 4000 " | .696 (15.3) | .680 (15.4) | .673 (15.2) | .661 (14.8) | .627 (15.2) |
| **Crankcase Blowby, cfm** | | | | | |
| 800 rpm | 1.58 | 1.91 | 1.97 | 1.87 | 1.82 |
| 1200 " | 1.54 | 1.78 | 1.76 | 1.82 | 1.74 |
| 1600 " | 1.38 | 1.60 | 1.71 | 1.62 | 1.76 |
| 2000 " | 1.37 | 1.52 | 1.56 | 1.63 | 1.74 |
| 2400 " | 1.39 | 1.55 | 1.58 | 1.64 | 1.85 |
| 2800 " | 1.82 | 2.50 | 2.57 | 1.89 | 1.83 |
| 3200 " | 2.28 | 2.52 | 2.57 | 1.85 | 1.79 |
| 3600 " | 2.37 | 2.57 | 2.68 | 1.82 | 1.75 |
| 4000 " | 2.31 | 2.40 | 2.52 | 1.79 | 1.70 |
| **Compression Pressures** | | | | | |
| PSI @ 200 rpm & 2000 rpm | | | | | |
| Cyl. 1 | 182-234 | 185-237 | 168-226 | 150-181 | 155-188 |
| 2 | 180-235 | 185-239 | 161-226 | 143-180 | 149-184 |
| 3 | 181-231 | 181-232 | 165-226 | 145-181 | 153-187 |
| 4 | 180-233 | 178-235 | 172-231 | 144-179 | 144-184 |
| 5 | 180-231 | 181-235 | 175-231 | 151-185 | 158-195 |
| 6 | 176-235 | 181-235 | 173-232 | 144-177 | 149-187 |
| 7 | 175-229 | 178-233 | 160-221 | 148-185 | 161-193 |
| 8 | 181-234 | 183-237 | 167-229 | 140-180 | 142-182 |
| Avg. | 179-234 | 181-235 | 168-227 | 146-181 | 151-188 |

(1) Corrected to 29.53 in. Hg. dry air press., and 100°F carb. air.

(2) From faired curves.

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1-25-63

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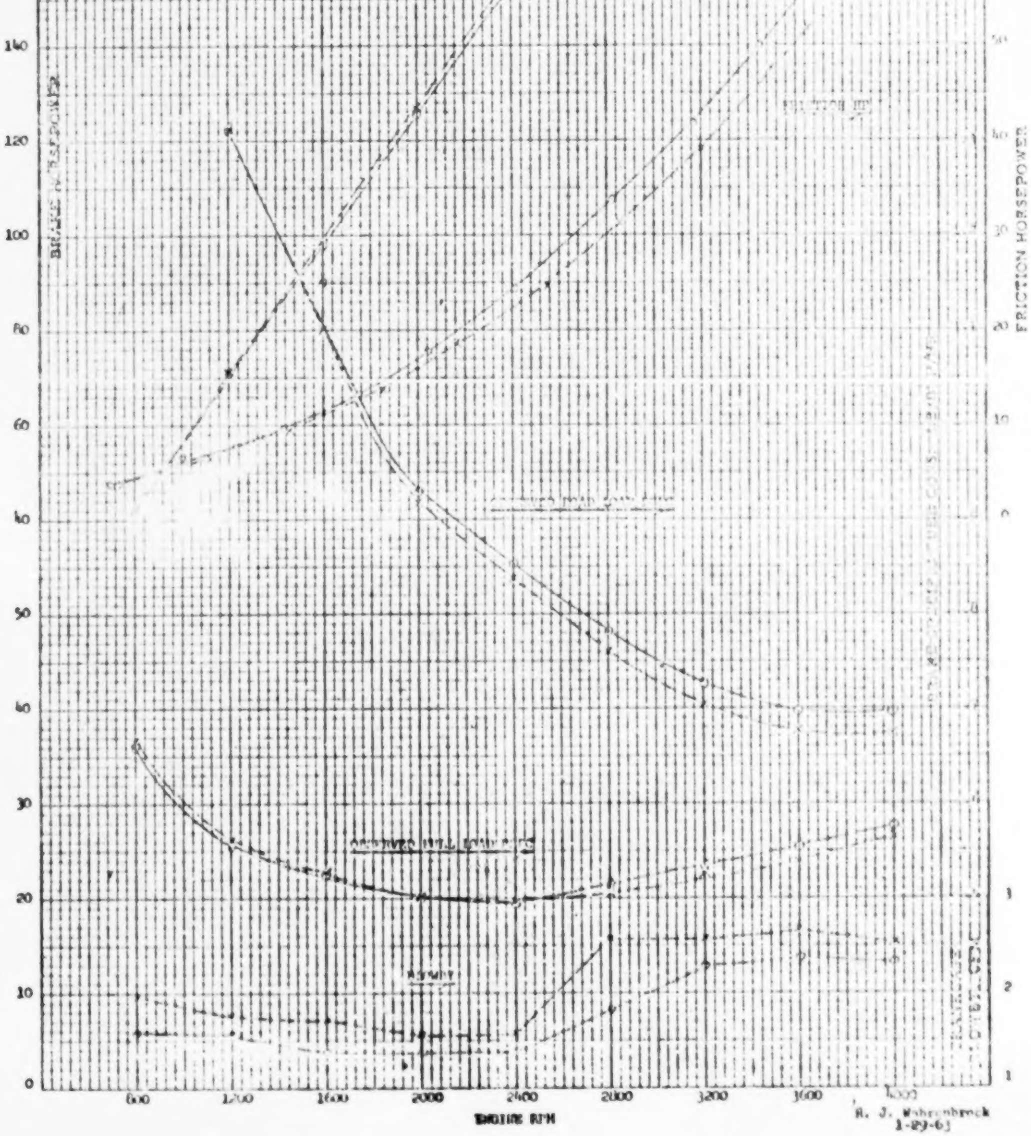
Ferndale, Michigan

Curve Sheet 1



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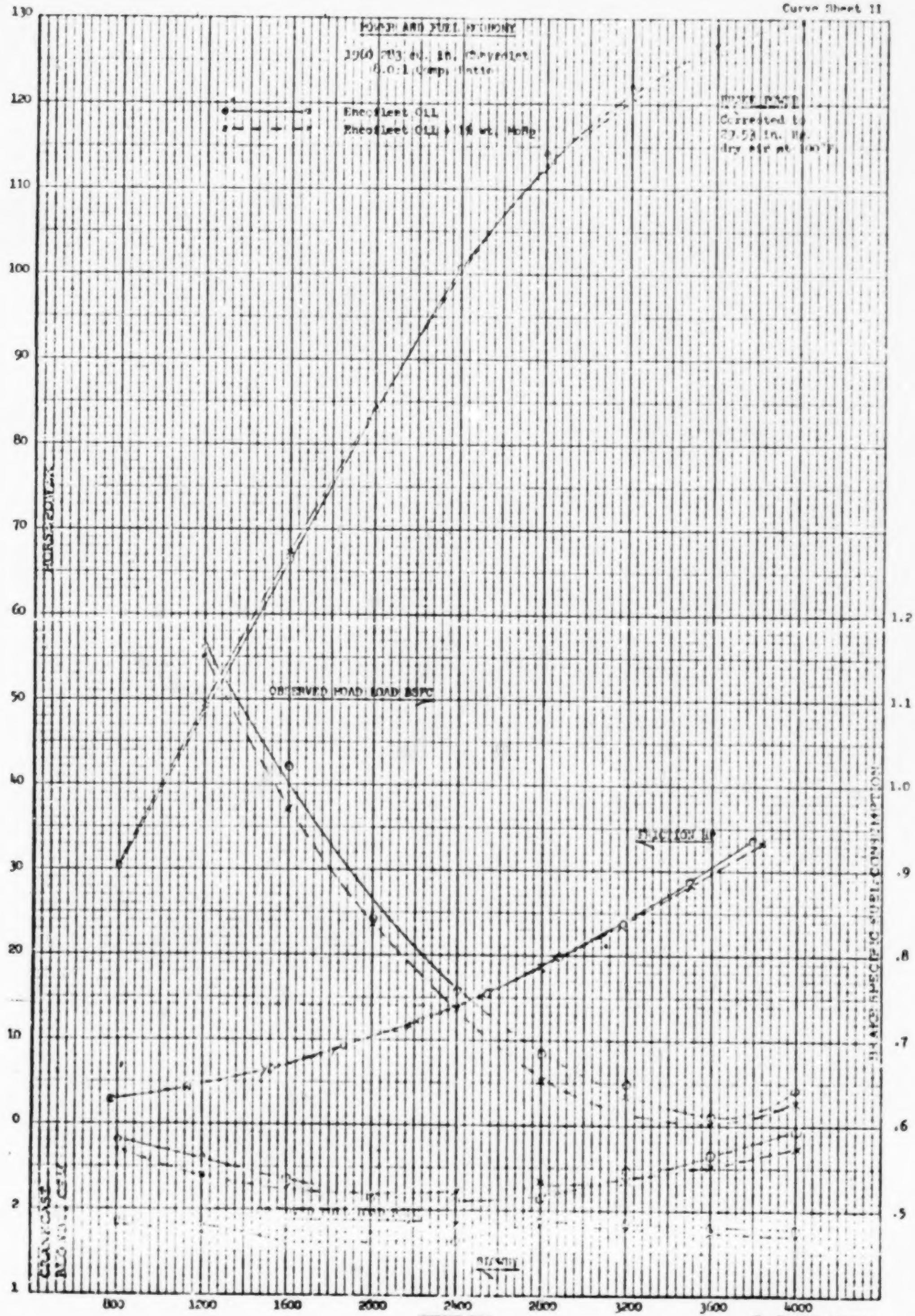
Curve Sheet II



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